6. Science Interests

6.1 Introduction

Astronomy is a science driven by discoveries. Our understanding of the cosmos is driven by discoveries that are powered by improved technology. The success of adaptive optics, a remarkably powerful technique for correcting the blurring of celestial images due to turbulences in the Earth's atmosphere, has enabled ground-based telescopes to achieve a resolution better than the Hubble Space Telescope. Today, leading observatories are exploiting the power of adaptive optics and other technologies to improve our understanding of the large-scale nature of the Universe and details of the many varied sources within it. However, what has also emerged is an understanding that even with these advanced technologies, today's large telescopes still lack the sensitivity and resolution necessary to study the most distant objects and their evolution, and to examine extrasolar planets with the necessary detail to see if life forms can be supported.

Though Indian astronomers have made a significant contribution to the understanding of the Universe, their efforts have been limited, largely by the modest facilities that are available to them. Access to the upcoming next generation of giant optical and infrared telescopes that will be able to observe objects nine times fainter than the existing 10-meter telescopes and with twelve times better resolution than the Hubble Space Telescope will go a long way in keeping Indian astronomy abreast with the international community.

The 30 m TMT, with a collecting area of 650 m^2 and adaptive optics capabilities will provide highly sensitive, diffraction-limited observations beyond 1 micron. With a capability to observe through the atmospheric windows from 0.31 to 28 microns, the resolution and sensitivity provided by the TMT's large aperture and AO systems, combined with the proposed suite of instruments, will enable us to address many of the most fundamental questions from the most distant realms of the Universe to our own Solar system. Figure 6.1 shows the sensitivity advantage that the TMT will have over the currently existing ground based facilities.

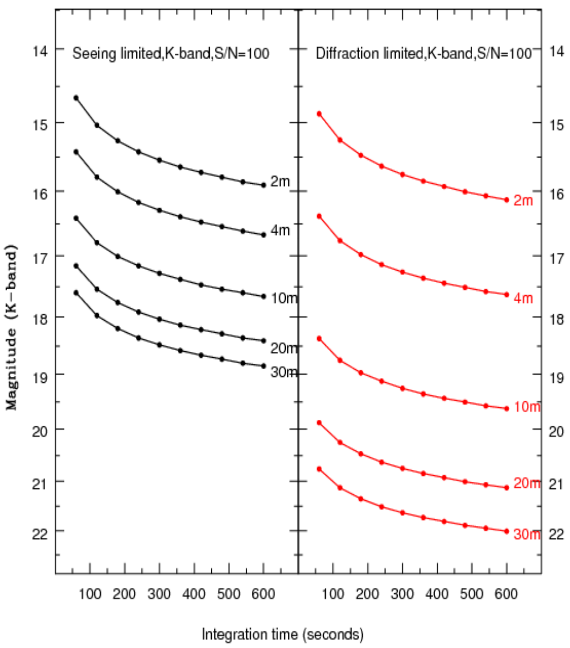

Figure 6.1: A comparison of limiting K (2.2 micron) magnitude that can be achieved with telescopes of different diameters (a) for the seeing limited (0.8")case (left panel), and (b) diffraction limited case that is achieved using AO (right panel). Note the remarkable increase in sensitivity with increasing diameter. A Strehl factor of 0.5 is assumed for the diffraction limited cases. (Figure: C.S. Stalin)

We detail in the following the key areas that are proposed to be addressed with the TMT. While most of these areas are those in which we already have significant expertise in, a few are envisaged on the basis of the new horizons that will be available only with a 30m class telescope. It may be borne in mind that powerful new facilities have often opened up unimagined areas of research and made important, but unanticipated discoveries.

Key Science Areas

- Formation and evolution of stars and planets
- Formation and evolution of galaxies
- The chemical evolution and composition of the Universe
- Stellar explosions and extreme physics
- The Early Universe

6.2 Formation of stars and planets

Stellar evolution is one of the most successful theories in astrophysics. This theory explains most of the basic observable properties of stars, and also accounts for the physical properties of stars through the various stages of their evolutionary stages. Despite this, there still is no clear understanding of the many details of the complex process of formation of stars from clouds of gas and dust, and from there to the formation of planets and the emergence of life. Indian astronomers have, during the past few decades, contributed significantly to the present knowledge of the formation and evolution of stars in our Galaxy and also in nearby galaxies. The use of TMT will aid resolve and understand better the complex processes of star and planet formation. A more complete understanding of star formation is fundamental towards understanding critical issues such as galaxy formation and evolution and the chemical enrichment history of the Universe.

6.2.1 Star forming regions and the Initial Mass Function

Star formation occurs in the denser regions of the interstellar medium comprising mainly of molecular gas and dust components. The (chronological) evolutionary sequences for the formation of low mass and high mass stars are expected to be entirely different, mainly due to the different time scales involved in various physical phenomena. At present, the low mass star formation is much better understood than the higher mass star formation. A generally accepted paradigm for the low mass star formation exists, which is very successful in explaining most of the observational details. There are several reasons for our poorer understanding about the higher mass star formation, e.g., they are very deeply embedded in dense interstellar cloud, shorter formation timescales, formation in clusters, etc. One of the more interesting premises connected with high mass star formation is the possibility that one generation of massive stars and its associated HII region could trigger further star formation as the HII region expands into the surrounding interstellar medium. Several processes linked to the expansion of an HII region may trigger star formation at their borders.

Recent observations indicate that some clouds produce dense clusters of hundreds of stars, while others form loose associations of a few stars. Within this diversity of clusters, the initial mass function (IMF) for ~0.2-30 M_sun stars is apparently universal, with little variation from cloud to cloud within the Galaxy. However, there are considerable variations at the lower and higher masses. Clouds with dense star clusters seem to form more brown dwarfs, and perhaps more massive stars compared to low density clouds with loose stellar associations. There is some evidence of variations in the IMF in nearby galaxies, where the high mass end of the IMF often appears top-heavy compared to the “standard” IMF (e.g. Figure 6.2: Ojha et al. 2009). In both local clouds and nearby galaxies, it is unclear as to whether variations in the high mass end of the IMF are real or due to sampling errors, while at the low mass end, searches for brown dwarfs and substellar objects have been limited.

If the differences in the IMFs at the high and low mass ends are real, the IMF is an important probe of the physics of star formation within molecular clouds and places limits on the mass-to-light ratio that can be expected in galaxies. These data also test the efficiency of star formation as a function of the initial conditions such as temperature, density and metallicity, and a measure of dynamical encounters within the evolving cluster. In order to establish the importance of initial conditions and dynamical interactions, large complete samples of clusters and star-forming regions in the Milky Way and other nearby galaxies will be required. Radio and sub mm observations that penetrate the large optical

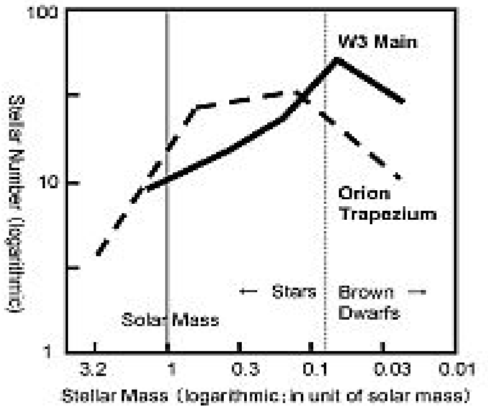

Figure 6.2: Stellar census showing population according to stellar mass. Horizontal axis is the mass in the unit of solar mass in log scale, while the vertical axis is the number of stars in log scale. In the W3 Main region (thick line), the population increases towards the less massive stars to the brown dwarfs, indicating an abundance of brown dwarfs in this region. Note that the turnover is in the more massive range in the Orion Trapezium cluster region. (D.K. Ojha et al. 2009)

extinction of dark clouds reveal the early stages of star formation process, but one has yet to learn what initiates the collapse or how the collapse evolves with time. Studies of the evolution of the gas will benefit from synergy between the observations in different wavelength regions.

6.2.2 Young Stellar Objects

The identification and study of young stellar objects which span a large mass range, is essential to understand the characteristics of star formation, like the duration, length-scale and the time required for the disruption of the molecular cloud. Identification and study of young stellar objects in the intermediate to low mass range is essential to understand their disk disruption timescales, modes of accretion, role of magnetic field in accretion, fraction of mass gained by the star by virtue of accretion (Bhavya et al. 2007, Subramaniam et al. 2005, Subramaniam et al. 2006).

Many recent studies have revealed that a large number of stars possess Beta-pic like disks indicating that disk dispersal does not take place rapidly. Also, many sub-stellar objects have been found to accrete through disks. All the above require identification and study of young stars in star forming regions (e.g. Ojha et al. 2009; Figure 6.3). The mechanisms of accretion differ with mass and it is still not clear how the most massive stars are formed, through accretion or clump mergers. It is also not very clear whether the accretion process takes place as a continuous process or in spurts.

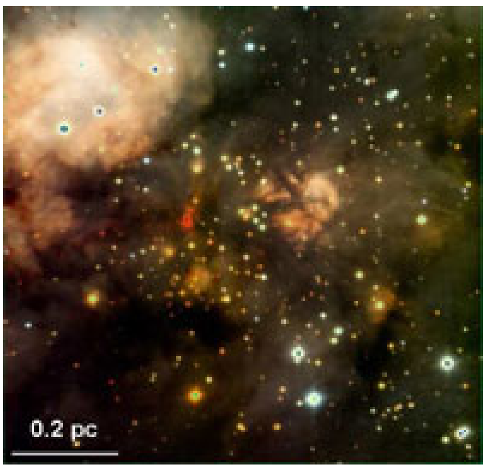

Figure 6.3: Subaru JHK composite image (red: K; green: H; blue: J) of W3 Main where massive stars are being born. Red objects to the left of the center are extremely young massive stars, surrounded by less massive stars that are one million years old. (Figure: D.K. Ojha)

The presence of magnetic fields around intermediate mass stars is still debated as this will alter the methods of accretion. As these stars have radiative envelopes, the source of magnetic field is also not clear. It is thus important to estimate the magnetic fields in these stars, which will be a fundamental input to stellar evolution theories. High resolution spectroscopic and spectropolarimetric observations would enable studies of the magnetic field.

Since the YSOs are shrouded by circumstellar material, these are in general faint in optical wavelengths. These are much brighter in the near IR, due to the excess radiation emitted by the heated circumstellar material. In optically identified clusters, YSOs are identified using this excess radiation in the near IR. Thus optical and NIR studies of star forming regions are necessary to identify the YSOs. Low to high resolution spectra will then used to identify the stellar as well as the disk properties. So far, YSOs are in general well studied only up to a distance of 1 kpc, with most of the studies done in the nearby Orion (~500pc) star forming region. A larger range in distance towards as well as away from the Galaxy will sample YSOs in a variety of star forming environments, including a range in metallicity. Such a variety is necessary to study the star formation properties as a function of the environment.

The TMT will probe the inner few hundred or 1000 AU regions of massive protostars. AO imaging and spatially resolved spectroscopy with the TMT will help probe the geometry and ionization state at unprecedented (~2-3 AU) scales, providing robust measurements of mass infall, accretion, and outflow rates as a function of time and stellar mass, velocity dispersions, masses and lifetimes of embedded clusters. This will allow us to understand the complex interaction between the star, disk, envelope, compact H II region and the bipolar cavities, and also better our understanding on these structures and how accretion proceeds to build the most massive stars of our Galaxy. Another question is if massive stars have binarity. This can also be done with the JWST, but the diffraction limit of the 30m telescope being much better than the JWST, especially in the mid-IR region, binary components are better characterized with the use of the TMT. The crucial bands would be between 8 and 20 micron where several high temperature lines and higher excitation lines of H2 molecule exist. JWST may be superior to a 30m ground telescope in terms of sensitivity at longer wavelengths but what is important is the high spatial resolution one can get with the TMT, in the same mid- and far-infrared bands to probe the small spatial scales.

6.2.3 Protoplanetary disks

The quest to discover earth-like/habitable planets has led to the discovery of several other planetary systems, which are completely unlike our own. The burning question now is to understand what makes these systems different from our own, to understand how planets are formed, what makes them habitable, and how do we discover habitable planets.

Protoplanetary disks are flattened rotating disks of gas and dust surrounding newly formed stars. Planets form within these disks as dust particles collect and grow by accretion. As the planets gain mass they attract surrounding gas, clearing a ring in the protoplanetary disk. Interaction with the disk circularizes planetary orbits, stabilizing the planetary system.

The inner ($r < 10$ AU) regions of protoplanetary disks are particularly interesting since these are the regions where most planets may form. These regions also intersect the habitable zone of their parent stars. Such inner disks are typically too small to be resolved, even by the TMT. However, Keplerian rotation of disks can be used to separate the disk regions in velocity, and hence radius, and derive radial variation of line intensity by fitting resolved line profiles. Making such separations in velocity demand high resolution spectroscopy. Given the temperatures of the disk, the spectral lines are expected to lie in the 1-25 micron region. Since these spectral features will have different sensitivities to density, temperature and abundance, those quantities can be mapped out along the entire inner disk.

6.2.4 Extra-solar (Exo) planets and planetary atmospheres

More than 200 planetary systems are known to exist beyond the solar system. A great majority of these have been found by detecting the small periodic motion of the host star due to the gravitational perturbation of its planets. Since the perturbation is proportional to the planetary mass, most of the planets that have been detected so far are massive gas-giants like Jupiter. Almost all known exo-planets have been discovered indirectly by measuring the reflex motions of their parent stars using radial velocity (RV) measurements. Detecting rocky, Earth-like planets in the habitable zones of cool dwarf stars requires radial velocity measurements with 1 m/s precision. Such precision measurements have been demonstrated using a very special instrument on the 10m Keck telescope. However, to reach the apparent flux limits for M stars wherein earth-like planets can be detected would require 1-3 hours per observation, severely constraining the number of stars that can be surveyed. With a 30m telescope, similar precision observations are possible in approximately < 10 mins for objects in the magnitude range V = 11-14. These shorter exposures will enable characterization of an entire orbital period (30-100 days) for tens to hundreds of candidate planets around early M dwarf stars in one year.

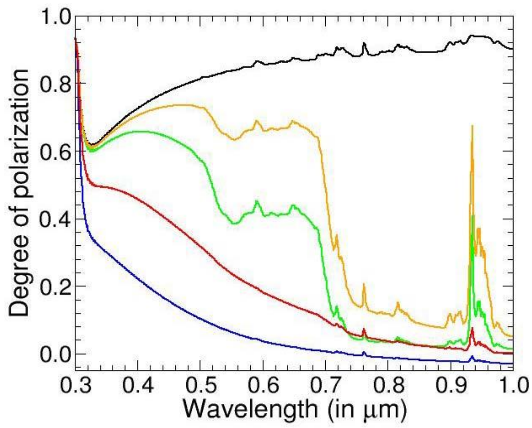

Fig 6.4. Theoretical spectra of a star hosting a habitable planet, showing the effect of vegetation on the degree of polarization – vegetation causes a decrease in the degree of polarization. The faint peak at 0.77 micron is due to O2 molecule and indicates the presence of life. (Figure: S. Sengupta)

Apart from the traditional methods of discovering planets by RV measurements and detecting light variation when a planet transits the host star, polarimetry is an extremely useful tool to detect exo-planets since the reflected light from these objects would be polarized due to scattering in the planetary atmosphere (Sengupta & Maiti 2006, Sengupta 2008). Polarimetric study can not only help in detecting earth-like small exo-planets, but also probe the presence of life in such planets. Since the planet-to-star flux ratio is very small (1 in $\sim 10^7$), the polarization of the system is expected to be very small (see Figure 6.4), necessitating the use of 20-30m class telescopes.

During transit, a small portion of the light emitted by the host star passes through the atmosphere of the planet. As a result, absorption features due to molecules in the planetary atmosphere are superimposed on the spectrum of the star. These features are extremely weak since only a very small portion of the light is affected by the atmosphere. However, the large collecting area of the TMT, together with a sensitive high resolution spectrograph would enable obtaining high S/N spectra of exo-planets from which one may extract signatures of water, methane etc.

6.3 Formation and Evolution of Galaxies

6.3.1 The Milky Way galaxy

Clues to the formation and evolution of our Milky Way galaxy are embedded in its building blocks – the stars. A systematic study of stellar motions and the composition are essential to reveal the origin and evolution of the Galaxy and its present structure. The Galaxy is broadly composed of three major structural components: the disk, the bulge, and the halo. Stars can be grouped into these components based on their kinematic properties, and their chemical composition (Eggen, Lynden-Bell & Sandage

1962). In addition to the above three components, the Milky Way galaxy is found to have sub-structures which are in agreement with the theoretical predictions for a hierarchical formation of the Galaxy via mergers. Understanding the different structures of the Milky Way - their origins, and dynamics, is one of the fundamental issues in astronomy. This clearly requires decomposing the components of the Galaxy based on the age, kinematics, and chemical composition of the stars.

For a decomposition of the Milky Way, measuring accurate astrometry (parallaxes, proper motions) and hence the kinematic motion for a large number of stars is essential. The Hipparcos Space Mission in 1998 provided accurate astrometry for around one hundred thousand stars in the solar neighbourhood (d <= 200 pc). Combining the ground based high resolution spectroscopy and the Hipparcos astrometry, the Galactic disk is decomposed into thin and thick disks (Reddy et al. 2003, 2006). Stars in the thick disk are old (~8- 10 Gyrs), metal-poor ([Fe/H]~-0.6) and are found to have distinct kinematic motions and chemical composition from that of the thin disk population. Abundances of elements with different nucleosynthesis history suggest that the thick disk stars formed mainly from SN II ejecta, and the formation of thick disk was rapid (<2 Gyrs) and there is no current star formation. The thick disk population is believed to be the result of a major merger of a metal-poor dwarf galaxy when the Milky Way was just 1-2 Gyrs old. There are many unanswered questions regarding the thick disk and the composition of the Milky Way galaxy: Is thick disk really a frozen entity? What is the metal-poor end of the thick disk? Are there any smaller components in the disk? What is the structure of the bulge and the halo?

To answer these questions one needs to measure astrometry for large number of stars beyond the Solar neighbourhood and obtain high resolution spectra for chemical tagging of individual stars. The space observatory GAIA planned to be launched in 2011 by ESO would measure astrometry for one billion stars up to m_v~20. Data is going to be available in the year 2015/16. GAIA will also measure radial velocities for a large number of stars. Together with astrometry and radial velocity, it would be possible to construct a 3-D view of our Galaxy and identify the distinct components based on kinematic motion. Chemical tagging of individual stars of different kinematic groups would help understand the evolution of the Galaxy in a chronological order, its merger history etc. Another proposed mission for astrometry, SIM (space interferometer) is expected to reach magnitudes limits fainter than GAIA and also reach farther distances. This would expand the scope of faint and old stars that can be observed with the TMT.

Young star clusters as well as HII regions are ideal tools to study the structure of the galactic disk. Present understanding of the Galactic disk is primarily based on what we know in the solar neighbourhood. Not many clusters are known beyond the 4 kpc radius. This would imply that we do not know much about the structure of the outer galactic disk, also, we do not know the structure towards the Galactic center.

It should be mentioned that most of the results for the clusters are currently based on observations using 2-4 m class telescopes (Subramaniam & Bhatt 2007). Therefore, systematic deep photometry of the disk is very essential to enhance the database of cluster population. A systematic study of their kinematics and abundances will give valuable data regarding the dynamics and abundance gradients in the disk of the Galaxy. Some kinematics and abundance studies are being done with the 8-m telescopes for clusters up to a few kiloparsec. Large aperture telescopes are required to study clusters more than 4 kpc away which helps to understand the initial mass function up to the low mass end, a fundamental parameter of star formation. Space velocity of all nearby clusters can be estimated and this can be used to identify streams and merger remnants in the disk.

6.3.2 Stellar population in the Local Group and nearby galaxies

The formation models of galaxies assume that all the galaxies, irrespective of their sizes are born with a halo comprising of population II stars. Direct detection of halo or the oldest stellar population and understanding the kinematic and chemical properties can be done only for the galaxies in the Local group. M 31 and our galaxy are the two galaxies in the local group for which a true halo population is traced. It turns out that these two galaxies are more massive than the rest of the local group members. It is thus necessary to examine whether the dwarf/irregular galaxies are also born with a halo. Among the smaller galaxies, the Magellanic Clouds (MCs) are our nearest neighbours. So far, we do not have a conclusive detection of the halo population in these galaxies (Subramaniam 2006).

The colour-magnitude diagram (CMD) of the LMC population at increasing distance from the LMC center indicates that, even at radii larger than the tidal radii, there is no trace of the halo population. The star counts are found to show an exponential behaviour. The halo, if it exists, can be detected by a 4 m facility, but will require a larger 6-8 m class facility to study the chemo-dynamic properties of the detected red giant population. On the other hand, large aperture telescopes are required to study red clump and main-sequence stars, and to study the stellar IMF down to 0.5 M_sun in the Magellan Clouds. Since the Clouds span a range in metallicity and star forming environments, the estimation of IMF in these galaxies up to substellar limit is of paramount importance.

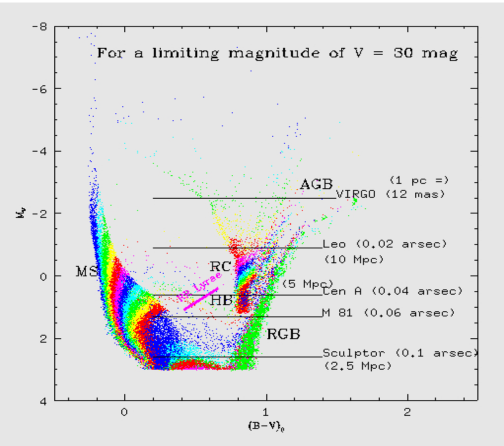

Figure 6.5. Synthetic CMDs of heterogeneous resolved stellar population in nearby galaxies. The horizontal lines indicate the type of stellar population that can be identified and studied at the various indicated distances.
(Figure: A. Subramaniam)

Chemo-dynamics and structure of the bar, disk, halo of the Clouds, extension of the Clouds and estimation of its dark matter content using stellar kinematics are some of the important studies that will help in understanding the formation and evolution of the Clouds. A study of the stellar population in the case of the rest of the galaxies in the local group and detection of the halo can be achieved with ease with the TMT. Such studies which help in understanding the chemo-dynamic properties of galaxies within the local group are expected to put stringent limits on the early galaxy formation models. As seen from Figure 6.5, it is possible to understand the kinematics and the dark matter content in the local group dwarfs, detect the halo population up to Cen A, AGB stars and the upper main sequence stars in the Leo group and identify individual stellar population in Virgo. The use of a multi-object spectroscopic instrument will enable observations of a large number of faint globular clusters in nearby ellipticals, up to a distance of 20 Mpc. The kinematical studies of several globular cluster systems around elliptical galaxies will help constrain the orbit structure and hence the dynamical mass as well as the halo properties.

The trigger for star formation in galaxies has been intriguing though several mechanisms such as spiral density wave, interaction and mergers, winds from supernovae and massive stars may all be aiding the process. Blue Compact Dwarf (BCD) galaxies are a class which exhibit recent star formation in the current epoch, and appear to have survived merging or any perturbation that would have led to an active past star formation history. They appear to have produced stars intermittently over the Hubble time (S. Ramya – Ph.D. thesis in progress). The BCD population is somewhat diverse and so is their evolution. The amount of dark matter in BCD galaxies is also of interest in testing various hypothesis regarding the stability of these HI-rich systems against perturbations that can trigger star formation. Studying the dynamics of BCD galaxies through high spatial resolution spectroscopy of individual stars and HII regions will be invaluable in this context. Analogues of the local BCDs have been detected in deep optical surveys out to z=0.8 (de Mello et al. 2006).

Since BCDs by definition are compact objects (scale-lengths < 4 kpc in most cases), high spatial resolution offered by adaptive optics is crucial to derive their velocity fields. The low surface brightness (LSB) galaxies are also a related class of galaxies having gaseous disks that are very stable against perturbations, and show very sparse star formation at the current epoch. It appears that some of them could be BCD galaxies in their quiescent phase, but others are comparable to normal galaxies in size and mass. Some of them even host an AGN which is contrary to the expectations from the well-known association between the central black-hole and presence of a prominent bulge. More detailed study of LSBs and BCDs is required to place them in proper perspective in the picture of galaxy evolution. Their faintness (surface brightness < 21 mag/arcsec^2) and small sizes (< few arcseconds) make it important to study them using 20-30m class telescopes equipped with adaptive optics and Integral Field Unit for mapping their velocity fields.

6.3.3 Baryonic Mass assembly in distant galaxies

One of the key issues addressed by galaxy formation theories is the physical processes that drive the galaxy mass assembly inside the dark matter halos. Did the most massive galaxies observed today form all their stars in a monolithic collapse (Eggen, Lynden-Bell & Sandage 1962) at a formation redshift z ≥10 and evolve passively thereafter? Or, did galaxies grow over cosmic time via hierarchical merging of low-mass galaxies at z< 1 (White & Rees 1978)? The hierarchical scenario has received wide-acceptance because of the good agreement of the semi-analytic model results and the observed evolution of galaxy properties, such as, luminosity function, clustering strengths, size distribution, etc (Cole et al. 2000; Somerville, Primack & Faber 2001, Samui et al. 2007). An important implication of this model is that the number density of massive galaxies must be significantly lower at z>1.

The recent ultra deep surveys using the Hubble Space Telescope, and Spitzer Space Telescope, have unveiled a remarkable population of galaxies at z> 5. These are massive galaxies with total mass in excess of 10^{11} M_sun, and ages several times 10^8 years (Mobasher et al. 2005; Rodighiero et al. 2007; Yan et al. 2006; Wiklind et al. 2008). Also, a gravitationally lensed candidate galaxy at *z*=6.56 has been reported with a stellar mass few times 10^{10} M_sun and an age of ~300 Myr. The existence of such massive, and evolved galaxies at *z*>5 when the Universe was only few 100 million years old, poses a serious challenge to the hierarchical scenario of galaxy formation, which posits that the massive galaxies were assembled at lower redshifts through major mergers of low-mass galaxies. Although, a few massive galaxies can be accommodated by the models, a major problem will unfold if the number density of massive halos expected to host these galaxies begin to exceed model predictions. If they exist in significant numbers, they would have very serious implications for galaxy formation scenarios, in addition to being potentially important sources of reionization. At the moment, we have no idea about the number densities of these objects because the current data do not offer a complete sample of the faint galaxies. In future, JWST with its exquisite NIR capabilities may reveal many more such candidates if they exist. From the observational point of view, the main drawback in the methods used to identify the massive, evolved galaxies is the use of spectral energy distribution (SED) template fits to the broad-band photometry with too many free parameters (age, extinction, metallicity, redshift, etc), and this method suffers from serious degeneracy. For example, as discussed by Wiklind et al. (2008), a generic feature in the SED fitting procedure is the presence of more than one local minima in two widely region of the parameter space; *z*>5 with little or no dust obscuration, and *z*=2 with E(B-V) ~0.5-0.9.

Most of the high redshift galaxy candidates, such as, the above mentioned red galaxies (Balmer-break galaxies), and the star-forming (Lyman-break galaxies) lack reliable spectroscopic redshifts. The luminosity functions, stellar mass distributions, and the inference on the cosmic star-formation history depend severely on the availability of accurate redshift measurements. At present, most spectra for high-z galaxies rely on emission lines for redshift determination, which is less successful in the case of post-starbursts and dusty systems. For example, only about 20-30% of the Lyman-break galaxies show a significant Lyman-α emission. Hence, it is important to make reliable measurements from the absorption lines, which in turn demands much higher signal-to-noise in the observed spectrum, for the absorption lines to be detected on the continuum. Absorption spectra of the candidates would be critical to confirm the redshifts, and quantify the fraction of massive galaxies at z>5 with evolved stellar populations. With the TMT, it will be possible to effortlessly obtain unprecedented high signal-to-noise in the absorption lines or continuum-breaks in the SED that can be used to determine independently the redshift as well as the age of the stellar population. The Balmer break at 3646 Å, and the absorption lines around this wavelength region can be targeted out to z>5. Large aperture (30-meter) telescope will be needed to obtain the necessary high S/N spectra, while the high spectral resolution offered by the back-end instruments will be crucial to remove the forest of IR sky lines efficiently and to reveal the spectral features from the galaxies.

6.3.4 Kinematics of star-forming galaxies at z=2-3

The redshift range *z*=2-3 is a crucial epoch to study the assembly of the Hubble sequence because current observations suggest that it marks the transition from the chaotic, and clumpy morphology seen at *z*>3 to the regular Hubble types seen at *z*=1. However, based on galaxy morphology seen in broad-band images alone, it has proven extremely difficult to distinguish kinematically-ordered disks from the major mergers (Ravindranath et al. 2006; Lotz et al. 2006). The role of mergers versus smooth accretion in galaxy transformations remains a matter of debate. Spatially-resolved two-dimensional velocity maps on the scale of tenths of arcseconds (corresponding to sub-kiloparsec scales at *z*=2), as obtained from Integral field spectrographs (IFS) is proving to be an efficient probe to identify disks and mergers (Law et al. 2007; Shapiro et al. 2008).

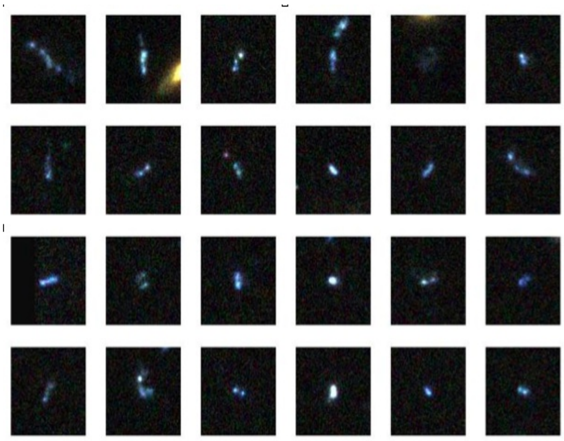

Figure 6.7 The diverse morphologies among the LBGs at z=3 in the GOODS fields (Ravindranath et al. 2006). Each image is 3 arcsec x 3 arcsec. A large fraction of these high-z galaxies show elongated or filamentary morphology. It is unclear whether these are high surface brightness star forming knots formed in the the cold gas disks or inflows, or are they multiple mergers of compact galaxies. Kinematic studies using the AO-equipped IFU instrument on the 30-m telescope will help to identify which of these possibilities actually explains the structure of LBGs. (Figure: S. Ravindranath)

Structural analysis of Lyman-break galaxies at *z*=3 using the Hubble Space Telescope images have revealed a large fraction of them to be disks or mergers, notably with high elongations that is suggestive of filamentarity (Ravindranath et al. 2006; see figure 6.7). In the recent hydrodynamical simulations of galaxy formation, the cold gas inflow in filaments is the dominant mode of gas accretion in low-mass dark matter halos at high-*z*, as opposed to the hot, spherical accretion in the high-mass halos (Keres et al. 2005). The observed filamentary or elongated morphology of Lyman-break galaxies appears to be consistent with this scenario of starbursts occurring via instabilities in a cold gas inflow. In order to verify this possibility, it is important to have velocity maps at high angular resolution using integral field spectrographs equipped with adaptive optics facility. The latter is particularly important because the high-*z* galaxies at *z*=3 have typical half-light radii 0.25-0.3 arc seconds (Ferguson et al. 2004). The sub-clumps within the chain galaxies that we are interested in, are separated by less than 0.1 arc seconds. This emphasizes that AO is absolutely necessary for us to map the velocity fields at high resolution using the emission lines from the individual star-forming regions (see fig 6.8: left).

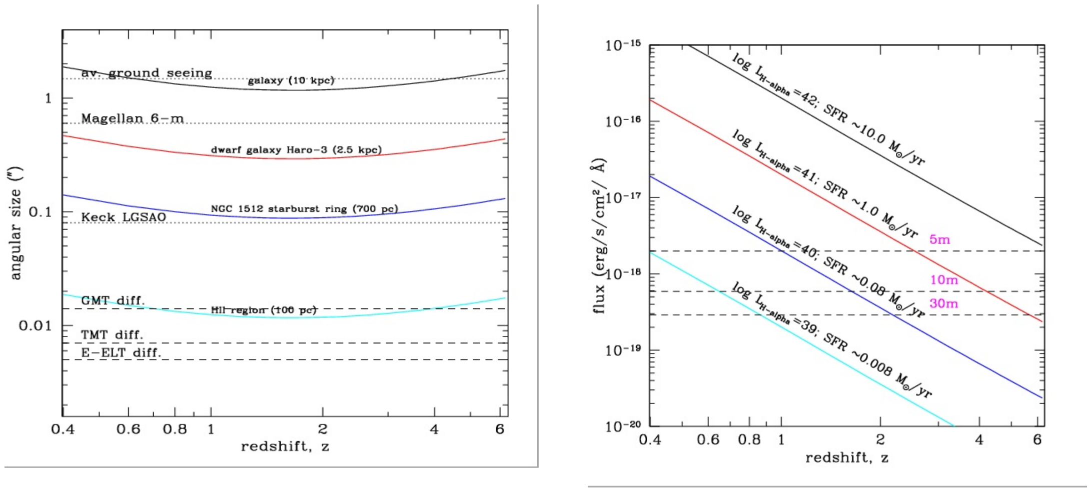

Figure 6.8. Left: Angular size versus redshift using the standard cosmology. Star-formation at various scales from individual galaxies (kiloparsecs) to individual star-forming or HII regions (parsecs) is shown. The dashed lines show the diffraction limit achievable on the GSMTs with use of adaptive optics, while the dotted lines show the resolution achieved with existing large telescopes. The angular resolutions offered by the 30-m class telescopes have parsec-scale resolutions out to high-z, which will allow to map the galaxy kinematics in unprecedented detail. Right: The expected Hα emission line flux levels for various intrinsic star-formation rates, is shown as a function of redshift. The Hα line luminosities corresponding to different SFRs are also marked. The dotted lines show the limiting sensitivities with various telescope apertures. As seen from the figure, 30-m telescopes can easily reach down to SFR = 1 M_sun/yr out to z=4, and to as low as SFR=0.08 M_sun/yr at z=2. The smaller aperture telescopes are only sensitive to the highest SFRs. (Figure: S. Ravindranath)

The current IFS observations done using the 10-m class telescopes make data analysis significantly difficult even for the brightest candidates because of the poor S/N in the spatial elements. Also, the sensitivity with existing telescopes only allows to probe the emission from the most luminous regions with high flux in the lines (eg; in H-alpha), which will tend to suppress an ordered disk rotation. Kinematics of distant galaxies will be one of the unprecedented strengths of the TMT because of the sensitivity to very low flux levels (see fig 6.8: right), the high signal-to-noise per spatial elements at milli-arcsecs resolution. With the spectrograph planned for the TMT, that have been optimized for performance in the near-infrared, we will be able to use the redshifted optical emission lines of H-alpha and OIII comfortably to *z*=3.

6.3.5 AGNs and the growth of super-massive black holes

In the last decade, there has been mounting evidence for the presence of super-massive black holes (SMBHs) in the centers of massive ellipticals and galaxy bulges (Kormendy & Gebhardt 2001). The various tight correlations observed between the SMBH mass and host galaxy properties has driven the idea of co-evolution of BHs and galaxy bulges (Gebhardt et al. 2000, Ferrarese & Merritt 2000). In the hierarchical paradigm of galaxy formation, an obvious consequence of galaxy mergers is the presence of binary black holes in at least few systems that can be caught in the act of merging. The BH pairs are expected to be initially separated by >1 kpc, and in about 100 Myrs they become true binary systems which are gravitationally bound to each other at parsec-scale separations. The orbital evolution of the binary BH happens via slingshot events on stars that approach the binary and are deflected to larger orbits, and have significant implications for the formation of cores in galaxy centers (Ravindranath et al. 2002, Milosavljević et al. 2002). As the scouring action by the BHs proceeds, the density in the center can become significantly low, leading to stalling of the binary orbit evolution for long timescales (few Gyrs). The final coalescence only occurs if the BH are close enough to emit gravitational radiation and merge rapidly. The binary BH theory predicts that almost 65% of the early-type galaxies are likely to have experienced stalling. Since an unambiguous evidence for the presence of BH is the associated AGN activity, the key observational evidence for binary BHs would be the presence of "twin or dual" AGN in a single galaxy formed via a merger. So far, there have been claims of direct detection of "dual BH or AGN" only in few nearby systems. The radio galaxy 0402+379 (Rodriguez et al. 2006) has a reported binary BH, and NGC 6240 (Komossa et al. 2003) has a dual AGN. In these few observed cases, the binary separations are fairly large, and may not have reached the stalling radius.

One of our aims is to use the TMT to search for binary BH signatures in nearby galaxies that exhibit cores. In Figure 6.9 (left) we show the computed stalling radius for nearby galaxies with measured SMBH masses. At the moment, we know the total BH mass, but do not have the resolution to confirm whether they have merged or exist as stalled binaries. The TMT will however, as shown in Figure 6.9 (left), have the required spatial resolution to probe down to the expected stalling radii of the binary BHs, which should manifest as "dual" AGNs. Also shown in Figure 6.9 (right) are the stalling radii for galaxies computed as far as the Coma Cluster (at 90 Mpc). It is seen that the TMT will be able to resolve the binaries, at least, in the most massive ellipticals.

From the context of galaxy evolution, it would be interesting if binary BHs could be identified at higher redshifts (z> 0.5) during a time when merging was dominant, and there is a higher possibility of observing the binary BHs with larger separation. The recent discovery of a dual AGN at z =0.7 (Gerke et al. 2007) in the DEEP2 galaxy redshift survey proves that high-resolution optical-NIR spectroscopy has the scope to reveal binary BH at high redshifts. However, these observations owe its success to various factors - the large 10-m aperture of Keck provides good S/N for the spectrum of a high-z source, the high spectral resolution offered by the DEIMOS instrument allows efficient removal of the sky emission lines, and the atmospheric seeing was fairly steady at 0.6 arc seconds throughout the observations.

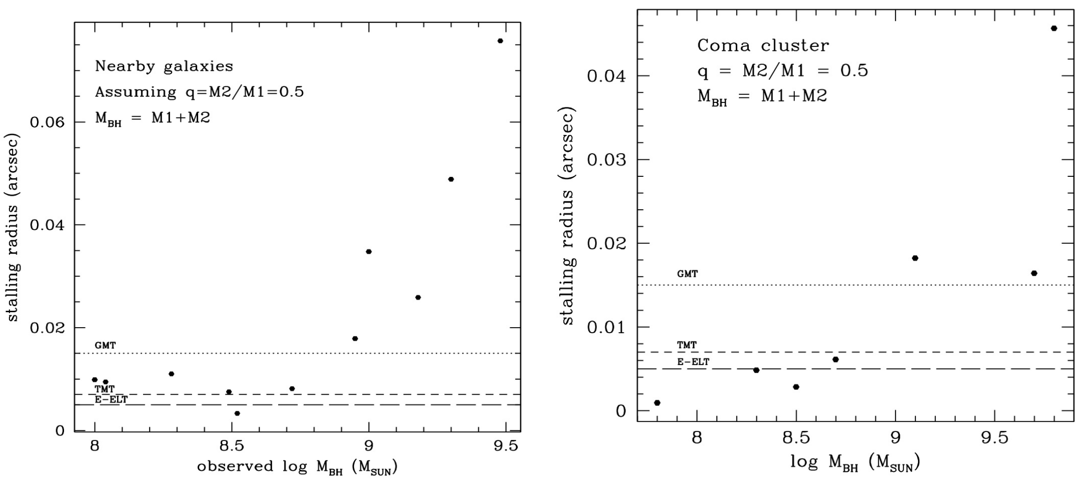

Figure 6.9. Left: The stalling radius for merging black-hole binaries is shown for the nearby "core" ellipticals with measured BH masses. The stalling radius is calculated following Merritt (2006), and assuming a black-hole mass ratio, q=0.5. Clearly, the radii are of the order of few milli-arcseconds, and the binary BH cannot be resolved using existing telescope facilities. With 30-m telescopes operating at the diffraction-limit, it will be possible to resolve the stalled binary black-holes if they are present. Right: The stalling radii for the most luminous galaxies in the Coma cluster which is located at 90 Mpc. The total BH mass (M_BH) has been derived from the known luminosities, by using the mass-to-light ratios for ellipticals, and the well-known correlations between galaxy bulge mass and BH mass. The stalling radii are calculated for mass ratio, q=0.5. With the AO-equipped 30-m telescopes, it will be possible to identify the BH binaries in the biggest galaxies in the Coma clusters. (Figure S. Ravindranath)

Assuming that a typical galaxy experiences a major merger every few billion years and the lifetime of the resulting binary BH with considerable separation is about 100 Myrs, it is expected that 3-5% of the systems should show dual AGN (Gerke et al. 2007). At higher redshifts, the fraction should be even higher. Long-slit spectroscopy of early-type galaxies with blue cores, optimized for search for activity in the galaxy centers, should reveal many more dual AGNs at high redshifts. The GSMT with its large aperture, and NIR capabilities, and high spatial resolution, will be ideal to extend the search for merging black holes out to z=2, which marks the peak epoch of AGN activity and galaxy mass assembly. What is most important will be to have sub-kpc scale resolution, and this calls for AO corrections to reach close to the diffraction limit on the 20-30 meter telescope. Studying the association of AGN activity and starformation and the role of mergers in AGN as a function of redshift out to the epoch of peak AGN activity will have to capitalize on the synergy between missions like the JWST, and the capabilities of the TMT for follow-up spectroscopy.

Several all sky surveys exist at radio wavelengths. More such surveys at low radio frequencies (< 300 MHz) are being planned with the Giant Metrewave Radio Telescope in India and with upcoming telescopes such as LOFAR in The Netherlands. These surveys are expected to be the deepest and highest resolution surveys at these low radio frequencies and hence detect millions of radio sources. The planned surveys are expected to generate thousands of candidate high-redshift radio galaxies with flux densities 10 to 100 times fainter than the present studies. It is to be noted that there are only TWO radio galaxies having redshift larger than about 4.5; one of them at z=4.88 and another one at z=5.19. It is important to discover more radio galaxies around z=5 or higher to understand the occurrence of AGN phenomena and blackhole formation in the early universe. The optical follow-up work on identification, redshift, spectra, nature of these faint objects require larger than 10 m class optical telescopes. The TMT would scientifically complement the planned deep low frequency radio surveys and the multi-frequency data would lead to cosmologically important results. Likewise, the proposed survey to search for new AGN and QSOs using the upcoming 4-meter International Liquid Mirror Telescope (ILMT) at Devasthal is expected to detect ~15000 candidate objects with B < 24 mag. Clearly, the light-gathering power of the TMT along with the high spectral and spatial resolutions are necessary to obtain the velocity dispersions and hence infer the central blackhole mass of these objects.

6.4 The Cosmic Chemistry

6.4.1 Nucleosynthesis in stars

A study of the chemical abundances of stellar atmospheres is extremely important as stellar atmospheres contain fossil records of the material from which they formed as well as the products of the nucleosynthesis in the stellar cores, that may have been brought up to the surface. Except a handful, almost all elements in the periodic table are synthesized in the stellar interiors and envelopes during hydrostatic and explosive burning. Hence chemical evolution in differing stellar populations such as red giants, supergiants, AGB and post-AGB stars, RV Tau stars, hydrogen deficient stars, chemically peculiar and metal-poor stars, traces the star formation history and age and also provides insight into the chemical evolution of galaxies and their interstellar matter. High spectral resolution (R>20,000) with a good S/N (>50) ratio are required for such studies, especially to detect and analyse faint spectral features. A 20-30 m class telescope will have a dramatic impact in nucleosynthesis studies as it will aid detection of faint spectral features and also open up hitherto unreachable classes of stars for study.

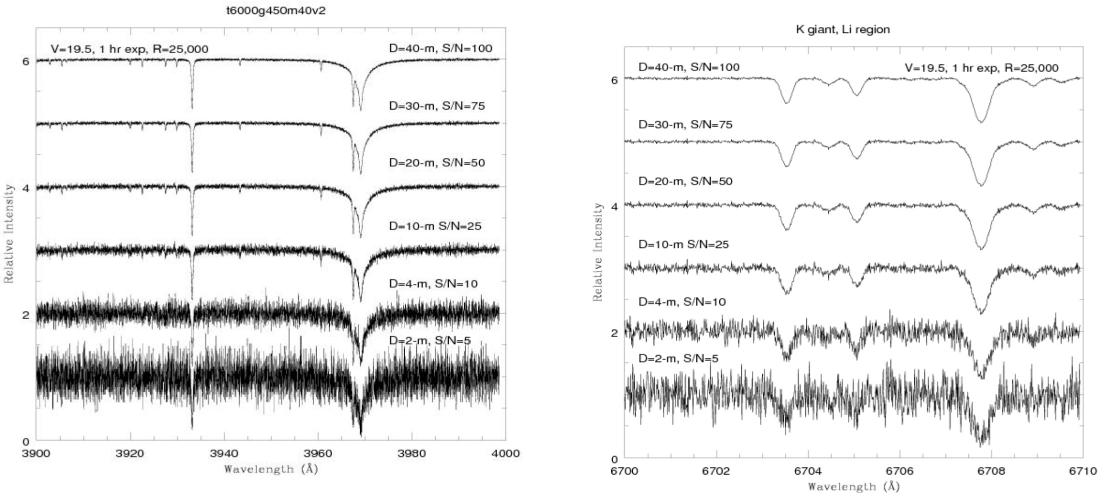

Figure 6.10. Simulated spectra showing the S/N that is achieved with telescopes of different sizes at a spectral resolution of R=25,000, for metal poor stars (left) and Li-rich K giants (right).(Figure: G. Pandey)

With the existing large telescopes, obtaining high resolution spectra with good S/N is very time consuming and most of the time one may not get the desired results. The 20-30m telescopes will be ~20 times more efficient which makes a good case to study a large sample of stars to understand stellar and primordial nucleosynthesis. Figure 6.10 demonstrates the strong need for large aperture telescopes even at a resolution of R=25,000. Plotted in the figure are simulated spectra of a metal-poor star and a Li-rich K giant that will be obtained with telescopes of different apertures. It is clear from the figure that with a 2-4 m class telescope, the S/N of the spectrum is such that only the very strong features can be detected, and thus telescopes of this class are suitable for a survey. For detailed studies, it is seen that while the S/N certainly improves with a 10 m class telescope, even this aperture is insufficient to do detailed elemental abundance analysis including the fainter features. *Only telescopes with apertures > 20 m are suitable for detailed spectroscopic studies.*

While elements are formed inside stars, some light elements such as D, Li, Be are also destroyed inside stars, under certain conditions. The detection and abundance estimate of these elements is important to understand the stellar structure, evolution and mixing process in stars and the amount of stellar processing. We discuss below some of the key problems in stellar nucleosynthesis.

Lithium Abundance

^{7}Li is one of the four isotopes produced during the big bang. Spite & Spite (1982) showed that metal poor population II stars show a constant Li abundance with a very low scatter. Since Li is destroyed in the hot interior and envelope of stars, the Li present in these stars could be the primordial value. However, recent WMAP determination of the cosmic baryon density, combined with the Big Bang Nucleosynthesis (BBN) theory, tightly predicts a Li abundance value that is a factor of two or more compared to the Spite plateau, observed in the halo stars. Several possible solutions, such as stellar destruction and astraction, nuclear uncertainties and new physics, atomic diffusion etc. have been proposed to explain the discrepancy. Another interesting problem is the abundance of ^{6}Li. This Li isotope is produced by cosmic ray spallation and is expected to show a correlation with metallicity. ^{6}Li is more easily destroyed in the stellar interiors compared to ^{7}Li. However, a study of metal poor stars shows an unrealistically high ^{6}Li, and also a plateau. This opens up the exciting prospect of a pre-Galactic origin of ^{6}Li, possibly due to cosmological cosmic rays, or late decaying massive particles in the Big Bang. It is, however, to be noted that any asymmetry in line profiles would lead to an incorrect abundance estimate. Hence spectra of extremely high quality, in terms of both S/N and spectral resolution are required for an accurate estimate.

An understanding of the Li problem and depletion processes inside stars may be achieved better by the study of metal poor globular clusters. With the existing 8-10 m telescope facilities, it is quite challenging to estimate the Li abundance in the faint main sequence stars. With the use of the TMT, it will be possible to study Li abundance even in the main sequence stars. Correlating the Li abundance with other heavy elements will help understand the discrepancy between the observed Li abundance compared to WMAP results.

An interesting aspect of Li abundance is the study of Li-rich K-giants. Very few stars have been detected in the solar neighbourhood that show enhanced Li abundance. Interestingly, all these stars lie in the red clump region, after the 1st dredge up phase (Balachandran & ...; Reddy et al. 2003; B. Yerra – PhD thesis in progress). The extension of the existing survey of Li-rich K-giants, and a detailed study of such stars beyond the solar neighbourhood would help in understanding the mixing processes in stellar interiors.

C, N, O elements and Beryllium

C, N and O are the most abundant elements after H and He. They are produced in all types of stars during hydrogen and helium burning. C, N, O elements play an important role in star formation by cooling the clouds through several fine structure lines. Recently, it has been found that metal poor stars show copius amount of C (Sivarani et al. 2004, Sivarani et al. 2006), which appears to increase with low metallicities. This is possibly an evidence of a gradual change in the characteristic mass of the IMF, which is likely to be mediated by CMB temperatures acting as a minimum temperature (Tumulison 2007). With the TMT it will be possible to look for such correlations in the local dwarf Galaxies and test the theoretical prediction.

Beryllium is produced by cosmic ray spallation of the C, N, O elements. Be abundances in the Galaxy and satellites of the Milky Way provide constraints on the pre-Galactic cosmic ray fluxes and cosmic magnetic fields. If Be and B are produced as secondary elements, one would expect a Be abundance to decrease quadratically with respect to metallicity. However, the observations of two dozen metal poor stars show that there is a linear decrease with metallicity (Primas et al. 2004), indicating a primary production of C, N, O and Be from the same mechanism. It is important to increase the sample of such objects to verify the correlation. The TMT will enable such studies out to fainter limits, extending the sample beyond the MilkyWay to the local group dwarfs.

Other elements

In addition to Li, Be and C, N, O, there are several other elements that are of prime interest, such as the r-process and s-process elements, and elements such as F that are destroyed in the stellar interiors.

The recent discovery of F (Pandey 2006; Pandey et al. 2008) in Extreme helium (EHe) and R Coronae Borealis (RCB) stars (Pandey et al. 2006) which are suggested to have gone through the AGB phase brought the issue of F synthesis in stellar interior to forefront. They showed F enhancement in these stars by factors of 800- 8000 relative to its likely initial abundance. The key issues to be understood are: a) exact synthesis mechanism of F and the prevailing conditions in the stellar interiors, b) evolution of F in the Galaxy with respect to Fe and also other elements: the F versus Fe trend is one important datum for inferring the evolved stars initial F abundance from their present Fe abundances. It is essential to measure F in stars of different metallicities, ages and evolutionary phases to pin down the puzzle of its origin and evolution. A 20-30m telescope equipped with a high resolution spectrometer will enable measurement of F using the IR HF lines in a large sample of K and M giants with a range of metallicities and ages.

To summarize, high resolution spectroscopy using 30m class telescopes will enable elemental abundance studies way beyond the currently possible galactic field stars, extending the sample to the stars at the fainter end of the main sequence in globular clusters and stars in local group dwarf galaxies.

6.4.2 The Earliest stars

The presence of the first generation of stars (or population III stars) has been long postulated. For the last three decades or so astronomers have been searching for these stars of the very first stellar generation in our Galaxy. Of prime interest are (i) the nature of the first stars that formed in the Universe, (ii) the nucleosynthesis events associated with them, and (iii) the first mass function (FMF) which is associated with the earliest star formation in the universe. In addition, the presence of such stars in the early universe has important implications to our understanding of the reionization process and early metal enrichment of galaxies and intergalactic medium.

The studies of metal-poor stars are likely to provide one of the few means by which one can obtain knowledge of the first stars and the FMF. Metal poor stars are, however, quite rare – only one out of a ten thousand objects in the Galactic halo is metal poor by a factor of ~3 compared to the Sun. The significant discovery of the two very metal-poor stars at metallicities [Fe/H] = -5.4 (Christlieb et al. 2003, Frebal et al. 2005) has raised new hopes to find more such stellar relics from the young universe and thereby study unpolluted big bang material. This discovery has led to detailed observational as well as theoretical studies of the two objects- however, questions still remain as to whether they are representative of the first stars. Answers to these questions must be sought from studies of a sufficiently large and well-defined samples of such very metal-poor stars at high resolution. New surveys of metal-poor stars, such as that planned in the UV with ASTROSAT will discover several faint stars that will require detailed spectroscopic studies in the optical for abundance estimates. While a survey to identify metal poor stars can be done at low resolutions, using the existing 2-10 m class telescopes, a detailed abundance analysis would require a of resolution R~60,000-1,00,000. Clearly, at such resolutions, the S/N required for detailed abundance analyses can be obtained only with the 20-30m class telescopes.

A complimentary way of probing the same issues is by studying the abundance pattern in the low metallicity gas that can be detected in the spectra of high redshift QSOs/GRBs/LBGs. In particular the large number of QSO spectra available in the SDSS allow one to pick candidate absorption systems at high-z that are suitable for probing the nature of star formation in the low metallicity gas. Some progress has been made using an 8-m class telescope . However, most of the interesting candidates in the SDSS QSO sample are faint and accurate measurements are possible only for C, N and O towards brighter QSOs. TMT is required to measure the abundances of other rare elements in such systems towards fainter QSOs.

6.4.3 Isotopic ratios – testing cosmic homogeneity

The isotopic abundances of several key elements are indicative of the nucleosynthesis in the early Galaxy. The carbon isotopic ratios have been widely used to infer the degree of mixing of internally processed material with the outer layers of stellar atmospheres (Spite et al. 2004). It will be possible to derive important clues into the evolutionary processes of carbon enhanced metal-poor stars by studying the range of carbon abundances and carbon isotopic ratios exhibited by them. In a similar way, MgH bands near 5140A, have also been used to infer the ratios of ^{24}Mg, ^{25}Mg and ^{26}Mg for metal-poor stars in the halo (Yong, Lambert & Ivans 2003) and in globular-cluster giants (Yong et al. 2003). The Mg isotope measurements are particularly important because they provide clues to the nucleosynthesis history of the star, i.e., whether its isotopic pattern arises from pre-supernova evolution of massive stars, or whether additional processes, such as the contribution from intermediate-mass AGB stars, are required (e.g. Goswami & Prantzos 2000). Such a study would therefore have great implications on the Galactic Chemical evolution.

Measuring the isotopic abundance of Mg at various remote locations of the universe (and over a range of metallicities) is also very important for the studies of variation of fundamental constants using Many-Multiplet method. As the centroid of Mg II$\lambda\lambda$2796,2803 depends on the isotopic combination, an ill-constrained isotopic abundance of Mg II can mimic cosmological variation of electromagnetic coupling constant α (Murphy et al. 2003; Srianand et al. 2004; Chand et al. 2004).

Measuring isotopic ratios requires very high resolution (R~150,000) spectroscopy of relatively faint objects. This is beyond the scope of 10m class telescopes and can only be done using very high resolution spectrometers with the TMT.

6.4.4 Galaxy-Intergalactic medium interactions and metal enrichment

Presence of metals in the Ly-*α* forest (with $z > 1$) is now well established though C IV (Tytler et al. 1995; Songaila & Cowie 1996) and O IV (Bergeron et al. 2002; Simcoe, Sargent & Rauch 2002) absorption lines detected in the echelle spectra of high-redshift QSOs. In the standard framework of ΛCDM models the Ly-*α* forest absorption lines originate from density fluctuations that are either in the linear or in the quasi-linear regime (Bi & Davidsen 1997; Choudhury, Srianand & Padmanabhan, 2000). Typical density of this region (10-4 to 10-5 cm-3) is not high enough to sustain in situ star formation. Thus, metals that may be present in these regions need to be transported from the neighbouring star-forming regions (eg. Samui, Subramanian & Srianand, 2008). The amount and distribution of metals in the Ly-*α* forest provides information on different feedbacks from star-forming galaxies. Till now direct detection of metal in low density (i.e log N(H I) < 14.0 that occupy roughly 60% of the Universe) IGM is not possible using 8m class telescopes. Though it is possible to have some clues using pixel statistics (Scheye et al. 2003), the results at present are inconclusive (See Aracil et al. 2004). Direct detection of lines is important for drawing important constraints on the metal feed back.

The cosmic density of carbon as inferred from C IV optical depth analysis (Songaila 2001; Schaye et al. 2003) shows little evidence for evolution over the redshift range *z*=2-5, with possibly a decline by factor of two above **z**=6. It is possible that not all metals are seen. Just as most metals are in the hot intra-cluster gas at *z*<1, metals could be in hot gas resulting from galactic winds at higher *z*, thereby not producing significant C IV absorption. Also the shape of the UV-background, and its evolution with *z*, is the main uncertainty in converting optical depth to metallicity. ***I***mproved constraints require the detection of many more transitions like C II, Si II, Si III, O II etc. using very high s/n spectrum (>100 per pixel) at high resolution (R~100,000) to eliminate this uncertainty. In particular for z>6 one requires near-IR spectroscopy with good s/n and R. These are beyond the capabilities of the present day 8m class telescopes.

What is the origin of the metals seen in the IGM? Are the metals due to galactic winds, or is some fraction the result of population III stars? This important question can be addressed by correlating metals seen in absorption with the presence of galaxies (e.g. Adelberger et al. 2003, 2005; Pieri, Schaye & Aguirre 2005). This can be done by probing the IGM with many sight lines, and requires obtaining spectra of fainter sources, including the brighter Lyman-break galaxies (LBGs) themselves. Current state of the art (Adelberger et al. 2005) is limited to measuring the mean metallicity in C IV as function of the galaxy's impact parameter using composite spectra; higher S/N≥50 per pixel moderate resolution (R~2000) should make it possible to look for metals in each individual galaxy spectrum and obtain good redshifts.

A better understanding of galaxy-IGM interactions is needed to constrain how feedback from stars and AGN affects galaxy formation as a function of redshift and galaxy mass. The redshift range 2<*z*<3 is well suited for such a study, as there are many lines in the observed optical-NIR part of the spectrum suited to ground-based observations, but a TMT is required to be able to observe fainter QSOs or brighter LBGs and dramatically improve the sampling with many more sight lines.

At z≥6 Ly-α forest becomes increasingly opaque, perhaps signalling the end of re-ionisation. If the IGM got polluted with metals through winds from low mass molecular cooled halos (or dwarf galaxies) then the only transitions that are detectable using optical near-IR spectroscopy are that of C IV, C II, O I, Si II and Si IV. The ionisation state of the IGM can be probed through the absorption produced by C IV, C II, O I and Si II (with NIR wavelength λ<2.1μ for z<12.5, 14.7, 15.1 and 15.7, respectively, e.g. Oh 2002) if the material cools efficiently. As the high-z objects are expected to be faint and the lines are shifted to IR it is important to have good IR spectrograph fitted in a TMT to get good s/n spectra of these distant objects. Detection of these lines puts stronger constraints on the models of structure formation in early universe. Given the rapidly declining space density of QSOs, Gamma Ray Bursts (GRBs) or supernovae could be used as background sources.

6.4.5 Molecules at high-z

Detecting H_2 and other molecules at high-z through their electronic transitions is important for understanding the physical conditions and astrochemistry in the interstellar medium of galaxies and protogalaxies at a very early epoch. Up to now, H_2 has been detected in 10 to 15% of Damped Lyman-α systems (DLAs) (see Ledoux, Petitjean & Srianand 2003; Noterdaeme et al. 2008). Detection of H_2 has allowed us to understand the physical conditions in the high redshift protogalaxies (Srianand et al. 2005). H_2 can potentially be detected from LBGs and GRB host galaxies. This will allow us to understand the interstellar medium in these early galaxies. *As the Lyman Werner band absorption line of H_2 are expected in the Ly-α forest, it is important to have high resolution R = 20,000 and signal to noise (>20) in the blue spectrum. TMT with a blue sensitive spectrometer will allow us to search for H_2 in fainter QSOs, GRBs and brighter LBGs*. However in the case of GRBs, H_2 may be in non-equilibrium and it is important to target the source as quickly as possible to be able to detect the H_2 lines and follow the time variation of H_2 column density. In addition, detection of vibrationally excited H_2 molecule will give important clues about the circumburst interstellar material around GRB hosts.

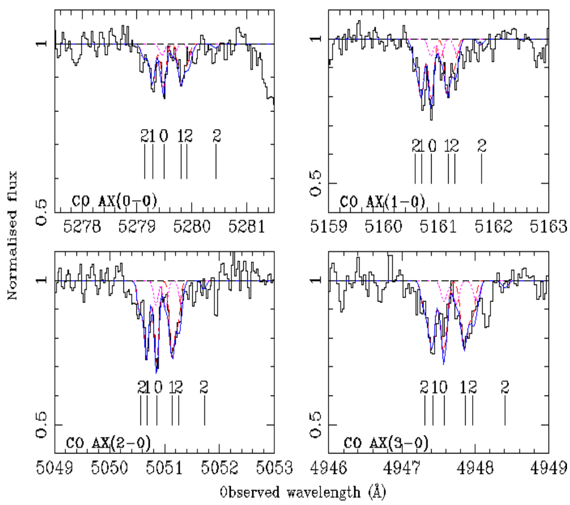

Figure 6.11. First detection of CO absorption at high-z (Srianand et al. 2008). The VLT/UVES spectrum and the Voigt profile fits to different rotational levels are shown. It is clear that at R~50,000 different J levels (tick marks) are unresolved. Higher resolution spectra are essential for detailed studies of such systems.

Detecting other molecules in systems with H_2 is also important for the understanding of astrochemistry in low metallicity gas in the early universe. HD has beed detected only in two cases till now and CO is seen in only two DLAs (see Fig. 6.8 , Varshalovich et al. 2001; Noterdaeme et al. 2008, Srianand et al. 2008, Noterdaeme et al. 2009). In all the other DLAs the achieved limits for CO detection are close to the lowest column measured in Milky Way. Searching for these molecules in front of red QSOs may yield better results. Different ongoing surveys with 8m class telescopes will provide a handful of QSOs with CO absorption. Getting spectra of such QSOs with R=100,000 and S/N>100 will enable one de-blend absorption from different J levels and to detect ^{13}CO (Burgh et al., 2007). Unlike H_2 absorption, electronic transitions of CO falls outside the Lyman-α forest, there by enabling its detectability even to a very high redshifts using deep NIR spectroscopy with TMT. This is very important for our understanding of galactic chemical evolution at high redshifts (see above). In addition, very high resolution NIR spectra of the dust reddened QSOs are needed to detect other complex molecules at high-z.

6.5 Stellar explosions and extreme physics

The most energetic stellar explosions, the supernovae (SNe) and gamma-ray burst sources (GRBs) are caused by the death of massive stars. The nature and evolution of the explosion and its remnant is determined by parameters such as the mass, metallicity and environment of the progenitor star. Figure 6.12 shows the luminosity and spectral evolution of the various types of supernovae observed in the low redshift universe.

The high luminosity of these objects enable their observations at cosmological distances and make them excellent probes to study the universe at various redshifts.

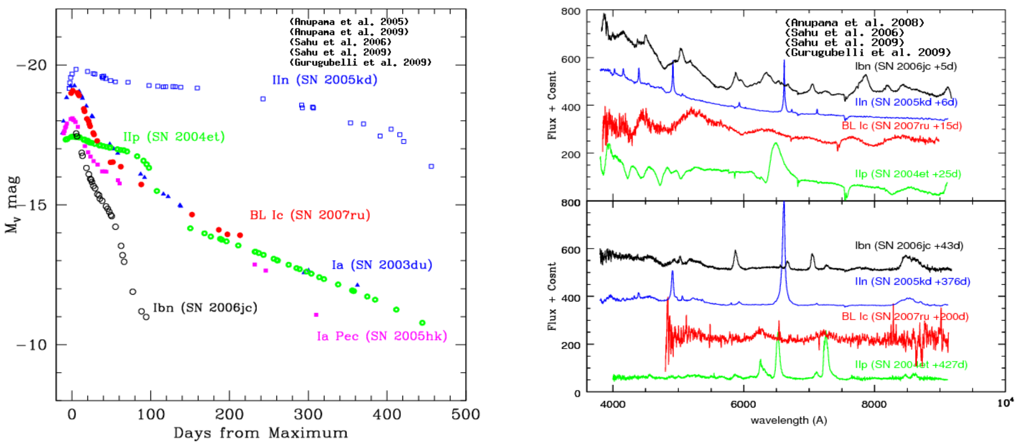

Figure 6.12. Evolution of luminosity (left) and spectrum (right) of SNe of different types. Based on observations of low redshift SNe. (Figure: G.C. Anupama, D.K. Sahu)

6.5.1 Core Collapse Supernovae as probes of stellar evolution

An important goal of studying core-collapse supernovae (CCSNe) is to deepen our understanding of the progenitors and explosion mechanisms of CCSNe. What kind of stars explode? What drives the explosion? Do CCSNe or their progenitors contribute significant quantities of dust to the interstellar medium (ISM)? What is the exact connection between Gamma Ray Bursts (GRBs) and CCSNe?

CCSNe, being the end stages of massive stars, are extremely good tools to probe the overall star formation history of the universe, and their observations at high redshifts would be a complementary test of cosmic evolution models. The observations of the sites of SNe would provide information on the progenitor population of these objects and also the star formation history of the region (e.g. Smartt et al., 2008). Recent observations of light echoes in supernova remnants have opened yet another method to determine the progenitors of supernovae. For example, light echoes from SN 1993J have been detected at the level of 22.3 magnitudes per arcsecond square by HST "V" band (F555W) observations. *TMT class of telescopes will detect light echoes to V ~ 28.5 mag/arcsec^2 in galaxies well beyond the Virgo Cluster*. With this capability one can determine the nature of SN types of all recorded explosions whose types (i.e. whether thermonuclear or core-collapse) are not known, in the past hundred years or so or of the SN remnants in the Local Group of Galaxies by faint object spectroscopy of the echoes of the light given out originally by the SN when it exploded. The classification of SNe and its progenitor and their properties are important to calibrate the distance scale and take a measure of the universe, including its dark energy contents and its early phase behavior and to study high-*z* supernovae upto the era of reionization. This line of research will determine the nature of the First SNe from the early generation of stars when the universe was quite young, e.g. z=6, and facilitate the use of Type IIp SNe as standard candles especially since in the early universe the present standards, i.e. type Ia's, may be more sparse than at low z.

Although traditionally optical observations have been used to study CCSNe (e.g. Sahu et al. 2006, Hendry et al. 2006, Utobin et al. 2007, Smartt 2009), in the recent past it has been shown that observations of these objects in the near-IR can test the nature of CCSNe in ways not available in other wavelength regions. Constraints on the CCSNe progenitor can be obtained with a combination of IR/optical photometry and optical-IR spectroscopy. Infrared spectroscopy during the photospheric phase can probe ejecta mixing and hence the explosion mechanism. Observations of CCSNe at late times phases provide a unique tool to understand the explosion mechanism and its geometry, since by these epochs, most of the ejecta can be directly studied. *A 20-30m aperture telescope will enable detailed studies of CCSNe upto z~1-2, while detection and spectroscopic confirmation of the brightest CCSNe (such as the type IIn) is possible at z~6.*

6.5.2 Pair Instability Supernovae

Pair instability supernovae (PISN) are thought to arise from extremely massive progenitors. Although PISN are rarely observed in the present, it is thought that they were very numerous in the distant past, among primordial, supermassive, low-metallicity population III stars. Massive stars, with an initial mass range 140 < M < 260 M_sun die in a thermonuclear runaway triggered by pair production instability. They release huge energy of the order 10^{53} ergs and may synthesize considerable amount of ^{56}Ni (upto 50M_sun). The PISN are characterized by peak magnitudes that are brighter than type II SNe and comparable, or brighter than type Ia. They have a long decay time (~1 year) due to large initial radii and large mass of material involved in the explosion. Hydrogen lines are present in these SNe, arising from the outer envelope. The massive stars that can retain most of their mass against mass loss are those that with metallicity close to zero ($Z < 10^{-4}$), and are hence expected at high redshifts. Metal enrichment is a local process, and it is possible to find metal free star-forming pockets at low redshifts (z~6). At z~2, the PISN/SN ratio is 4-10 times higher than locally, for Z=Z_sun/3 and Z=Z_sun/10, respectively (Langer & Norman 2006, Langer et al. 2007). A study of PISN will help in understanding the history of chemical enrichment, the nature of metal free stars and the evolution of gaseous matter in the universe (Scannapieco et al. 2005).

6.5.3 Supernovae-GRB connection

Some SNe Ibc, characterized by a very high kinetic energy (Iwamoto et al. 1998, Nomoto et al 2004), have been observed to be linked with GRBs. A jet like explosion is required for GRBs from energetics considerations, indicating asphericity in the explosion mechanism. Though evidence is accumulating that some classes of GRBs are connected with the deaths of a subset of massive stars, their connection with CCSNe is still largely unexplored barring a few events. Ordinary type Ib/c SNe are clearly distinguishable from the ones associated with the GRBs/XRFs in terms of the relativistic ejecta produced by the central engine. The GRBs/XRFs associated events couple bulk of their energy to relativistic ejecta whereas ordinary SNe Ibc couple less than a percent of their total energy to the fast material. Still we do not understand fully that what are the progenitors of SNe Ib/c and how do they differ from those associated with GRBs. However, the link to GRBs is a strong hint that GRBs/XRFs associated events could be significantly aspherical. If a jet is produced by a collapsing star, it can only emerge and generate GRB if the stellar envelope does not interfere with it, which is most likely in case of stripped envelope SNe.

There are some cases of low redshift type Ib/c supernovae with broad lines typical of hypernovae but not always associated with large luminosities typical of hypernovae (e.g. Valenti et al. 2008, Sahu et al. 2009). For these objects, the connection with GRBs is unclear or absent. The high velocity sets them apart from a typical SNe, with the only similar objects being the SNe associated with GRBs. These may be events where either the explosion was not strongly aspherical, or that it was viewed far from the jet axis (Mazalli et al 2005). *A study of the line profiles in the spectrum during nebular phase, together with spectropolarimetric observations* can help solve the mystery. Such studies *will benefit immensely with the use of the 20-30m class telescopes as it will enable detailed line profile* *studies at the late nebular optically thin phase, when the SN is normally 6-7 magnitudes fainter than its magnitude at maximum.*

6.5.4 GRB host galaxies

Gamma Ray Bursts still lack a direct identification of their progenitor stars. The evidence of what gives rise to GRBs therefore remains circumstantial. One important input to this body of evidence comes from the study of their host galaxies, and wherever possible, that of the immediate stellar neighbourhood of the GRB. The GRB sample goes out to high redshift: the measured GRB redshifts at present have a median value of 2.7. The host galaxies of GRBs that have been detected to date have their redshifts in the range 0-6.3, with a median of 0.8.

Clearly, a large fraction of the high redshift GRB host population remains to be discovered. *The majority of the known hosts have magnitudes in the range R~22-27 and K~20-25, close to the limit of studies possible with the present-day 10-m class telescopes (Savaglio et al 2008).*

The TMT class telescopes will have an excellent opportunity to address the question of the nature of GRB hosts. In addition to increasing the sample size at the high redshift end, these telescopes will enable detailed spectroscopic studies of the host galaxies to be carried out. At present multiband photometry of GRB hosts is being used to fit synthetic spectral models, from which the mass, metallicity, age and star formation rate are being deduced. The derived values suffer from very large uncertainties, making it difficult to reach definite conclusions regarding the nature of this galaxy population. *TMT will enable one to study these objects spectroscopically, enhancing the reliability of model fitting and parameter extraction manifold. The present viewpoint that GRBs originate in sub-L_*, actively star-forming galaxies with low metallicity can be seriously tested only by such detailed spectroscopic study.*

Morphological classification of GRB hosts, carried out mainly using the HST (Wainwright et al 2007), seems to suggest a preponderance of irregulars among them. *The enhanced angular resolution of the TMT compared to the present day ground based telescopes can be put to use in conducting such morphological classification of a larger sample of GRB hosts. This may throw some light on whether the GRB production rate is influenced by galaxy mergers.*

In favourable circumstances, the TMT class telescopes will allow spatially resolved spectroscopy of the GRB host to be performed, as has been done now for the hosts of two low redshift GRBs (Thoene & Fynbo 2007, Michalowski et al 2008). These studies reveal that even in galaxies with regular metallicity, the immediate neighbourhood of the GRB appears to harbour a low-metallicity star-forming region. So the overall metallicity of the galaxy itself may not be a complete indicator of the star formation process that leads to a GRB progenitor. Extending this study to a larger sample, especially at high redshifts, is therefore necessary to establish the correlation of GRBs with low-metallicity progenitors. The TMT, with the combination of AO and Integral Field Unit will be invaluable for such studies.

6.5.5 Low mass X-ray binaries, neutron stars and pulsars, white dwarfs

Low mass X-ray binaries (LMXBs) are systems that consist of an accreting neutron star or blackhole, with a low mass companion. Many of them are transient sources in the X-ray. Optical counterparts have been detected only in a few LMXBs. It is expected that the ASTROSAT will discover several new LMXB systems. A study of the optical light curves and a measure of the radial velocities in these systems are important as these will constrain the mass of the compact star, i.e. The blackhole or the neutron star, the inclination angle of the system, and the radius of the companion star. The TMT will enable these studies of LMXBs upto 10 kpc.

Jets are detected from some blackhole LMXBs. One exciting possibility is that such jest are (atleast partially) powered by the spin of blackholes. If true, this will test several aspects of extreme physics, including string gravity, and can be verified when the mass and angular momentum of a jet producing blackhole is known.

While nearly 1500 radio pulsars are known, only a few "ordinary", isolated young neutron stars have been observed in the optical. Also, no millisecond pulsar has been detected so far in the optical, even with the 10m class telescopes. At magnitudes of V ~ 23.0 or fainter, the optical radiation detected so far suggests a thermal, rather than a magnetospheric origin. Thus optical studies of radio bright neutron stars provide important information on the rate of cooling. Coupled with independent, spin down measurements of the age, the cooling rates can be used to constrain models of the NS structure, and therefore highly neutronised matter at high densities. Clearly, a TMT class telescope is required to study such objects in the optical.

TAUVEX and ASTROSAT are expected to discover/detect several new white dwarfs, several of which are expected to be fainter than V>20 mag. The optical studies of these objects would require a TMT class telescope.

6.6 The Early Universe

6.6.1 Cosmology with Ly-α *forest*

The large-scale flux distribution can be used to infer the dark matter power spectrum (Croft et al. 1998; McDonald et al. 2000; Viel et al. 2004) and constrain the neutrino mass (Croft et al. 1999; Viel et al. 2005). These measurements are currently limited by uncertainties in the shape of the QSO's underlying continuum, calibration of the echelle spectrograph for high resolution spectra, and by the statistics of available spectra, and would not obviously benefit from an TMT. However, the influence of large-scale structure is also very prominent in simulations at *low* optical depths. Such observations require much higher S/N than currently available, since even S/N=50 data cannot recover the median optical depth at z~2.

Observations of the forest along parallel sight lines can constrain the topology of the Universe via the Alcock-Paczynski (1979) test (e.g. Rollinde et al. 2003). As projected separations between QSOs are large, Alcock-Paczynski test could not be used to get stronger constraints on the topology of the universe. However, spectroscopic observations of large number of high redshift Galaxies using a TMT fitted with Multiobject spectrograph with moderate resolution (R~2000) will provide good spatial coverage. These observations will complement SNe data at low-z and CMBR data. In addition these observations will enable one to recover power-spectrum using both transverse and longitudinal correlations. This is an important step in cosmology as unlike line of sight correlations transfers correlation is not affected by the peculiar velocities. The required data could be obtained as a part of spectroscopic survey of galaxies using multi-object spectrographs (see before).

6.6.2 Probing the fundamental physics

Current laboratory constraints exclude any significant variation of various fundamental dimensionless constants in the low-energy regime. It is not excluded however that they have varied over cosmological time-scales. Savedoff (1956) first pointed out the possibility of using redshifted atomic lines from distant objects like QSOs to test the evolution of dimensionless physical constants and the technique was first used by Potekhin & Varshalovich (1994).

Murphy et al. (2003) claimed that at z~2.1, α was smaller than it is today with $\Delta\alpha/\alpha \sim 0.5\text{x}10^{-5}$ using metal absorption lines seen in the spectra of distant QSOs. However, a systematic analysis of higher S/N ratio (~70 per pixel), higher spectral resolution (R>45000) UVES data of 23 Mg II systems detected toward 18 QSOs in the redshift range $0.4<z<2.3$ has resulted in a non-detection of any significant variation, $\Delta\alpha/\alpha = (-0.06\pm0.06)\text{x}10^{-5}$ (Srianand et al., 2004; Chand et al., 2004). However, the debate is not settled yet and a strong controversy has opposed recently the two groups (Srianand et al. 2007; Murphy et al. 2007).

In any case the constraints based on QSO absorption lines obtained using 8m class telescopes are two orders of magnitude weaker than that achieved in the laboratories (see Fig 6.13 for a summary of all the available measurements till date) . Higher resolution (R>100,000) and good signal to noise ratio

(>100 per pixel) are needed to improve the precision. Echelle spectrograph operating in the near-IR will enable one to perform similar analysis with Fe II transitions at high redshifts (i.e z>2).

The variation of the proton-to-electron mass ratio (μ) can be constrained using the observed wavelengths of H_2 electron-vibro-rotational line (Varshalovich & Levshakov, 1993). Recently Ivanchik et al. (2005) obtained $\Delta\mu/\mu = (1.65\pm0.74)$ x10^{-5} using 80 H_2 absorption lines toward damped Ly-α systems at z_{abs}=2.947 and 3.024 towards Q0405-443 and Q0347-383, respectively. Using the same data and improved laboratory wavelengths Reinhold et. al. (2006) derived $\Delta\mu/\mu = (2.0\pm0.6)$ x 10^{-5}. However, this claim has been questioned by a recent study of the same QSOs by King et al. (2008). The difference in the analysis of same data arises mainly due to Voigt profile fitting procedure and number of components used. This uncertainty can be lifted if one has very high resolution (R~100,000) and signal to noise spectrum ~100 per pixel of hand full of QSOs. With 8m class telescopes it is nearly impossible to get such data for high-z QSOs that are usually fainter than 17 mag. One requires >20m class telescopes fitted with good quality echelle spectrograph that has very good internal wavelength calibration.

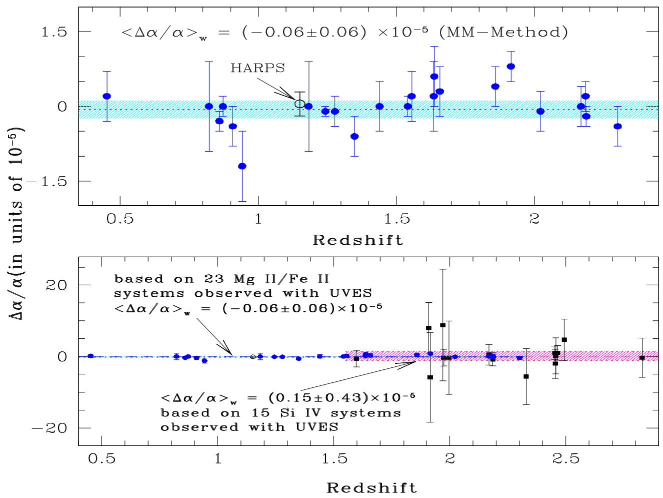

Figure 6.13. Available constraints on the time variation of α obtained by the Indian group using the European Very Large Telescope (VLT) (Ref: Srianand et al. 2004, Chand et al. 2004, 2005 and 2007). Very high resolution (R~100,000) spectra of high-z objects with good wavelength stability (achieved with laser frequency combs) will enable one to improve the precision by an order of magnitude. Such improvements are needed to reach the sensitivity similar to the one obtained in the laboratories using lasers.

Studies based on molecular absorption lines seen in the radio/mm wavelength range are more sensitive than that based on optical/UV absorption lines only. They provide constraints on the variation of a combination of α, μ and the proton g-factor (G_p). All the existing observations are consistent with null detections (eg. Kanekar et al. 2004). The Square Kilometer Array (SKA) will measure the 21-cm line in most of the DLAs. The wavelength of the transition depends on α, μ and the proton g-factor and can provide a combined constraint on the variation of all these fundamental constants (see Tzanavaris et al. 2007). Detecting H_2 and weak transitions of Mn II, Ni II in DLAs with high signal to noise and resolution will allow lifting the degeneracy between the allowed variations of different fundamental constants that decide the shift of 21 cm absorption line. To avoid the systematic effects caused by the small-scale properties of the lines we require high resolution and high signal to noise to improve current constraints. To study the redshift evolution and to be able to use different sets of lines from the same system, it is of paramount importance to have a wide wavelength coverage (≥4000 Å). *Probing the variation of fundamental constant is one of the Key projects of TMT. It is important to note that one of the two leading groups in this field is from INDIA.*

6.6.3 CMB Temperature

The CMBR is an important source of excitation for those with transitions in the sub-millimeter range. This is the case for atomic species whose ground state splits into several fine-structure levels and of molecules that canbe excited in their rotational levels. If the relative level populations are thermalized by the CMBR, then the excitation temperature gives the temperature of the black-body radiation. It has long been proposed to measure the relative populations of such atomic levels in quasar absorption lines to derive T_{CMBR} at high redshift (Bahcall & Wolf 1968). Using 8m class telescopes now it is possible to determine the CMB temperature at intermediate redshift using the fine-structure excitation lines of carbon in DLAs, which is excited by CMB photons (see Srianand et al. 2000). Detecting C I absorption lines from the low density regions, where the collisional excitation will be sub-dominant using high S/N spectra will allow one to directly map the redshift evolution of temperature of the CMBR. However the method using atomic fine-structure lines involves modelling of ISM physics very accurately.

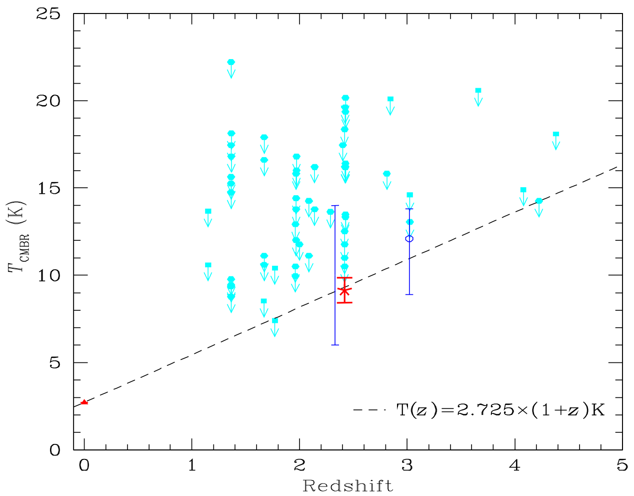

Figure 6.14. First detection of CO absorption at high-z (Srianand et al. 2008). The VLT/UVES spectrum and the Voigt profile fits to different rotational levels are shown. It is clear that at R~50,000 different J levels (tick marks) are unresolved. High resolution spectrograph in TMT is essential for detailed studies of such systems.

6.6.5 The epoch of reionization and the GRBs

The epoch of reionization is characterised by the epoch when the first stars began to form, providing the first sources of light and heat in the Universe after the Big Bang. The direct investigation of this epoch, usually accomplished by the observations of high redshift quasars, has, in the recent years been revolutionized by the observations of GRBs. As the end products of massive stars, GRBs briefly outshine any other source in the Universe and can be easily observed at cosmological distances. The recent discovery of a GRB at a redshift of z~8.3 (Tanvir et al. 2009, Salvaterra et al. 2009) well beyond the redshift of the most distant spectroscopically confirmed galaxy and quasar establishes that massive stars were being produced and dying at these epochs. This *recent detection of the distant GRB using 4-10 m class telescopes clearly indicates that it is possible to detect and study in great detail GRBs at much farther distances of z~10 using the 30m telescope*. GRBs being associated with individual stars, serve as signposts of starformation at the early epochs, they can also provide a measure of the neutral fraction of IGM at the location of the burst. *The observations of several GRBs at z >7 would provide multiple lines of sight through the IGM and thus allow us to trace the process of reionization from its early stages.*

6.6.6 Dark energy and the high-redshift supernovae

The greatest challenge facing cosmology and the quest for a more fundamental theory of the Universe lies in understanding the nature of dark energy. The standard model fails to account for the observed small value of the vacuum energy density. Much of the current observations focus on the measurements of the energy density and equation of state of the dark energy, which is often reduced to two parameters, *w* and *w'* which can be constrained through combined observations of supernovae, the cosmic background radiation and large-scale structure (e.g. Perlmutter 2005). Interestingly, a broad range of theoretical models are consistent with the observed data.

The light-curve-shape/luminosity relationship in SNe Ia make them extremely good standard candles and the most useful distance indicators at cosmological distances. They have been a key element to the discovery that the Universe is accelerating and dominated by dark energy (Riess et al. 1998, Perlmutter et al. 1999). Two questions that arise in the study of the dark energy are (a) is the dark energy density constant ($1+w = 0$, a cosmological constant) or not and (b) are the dark energy properties, as described by w, constant in time or not. Riess et al. (2007) find that below z~0.4, $1+w$ does not vary. In order to be able to provide meaningful constraints on the long term time evolution of $1+w$, observations of a large number of high-z (z~1.5) supernovae are required. The light curves of supernovae at high redshifts require accurate host galaxy correction and currently are best done from space. *However, the TMT with AO capabilities will be able to clearly resolve the SN from the host and will provide more accurate host galaxy correction, providing a large number of SN samples that will enable a more detailed study of the dark energy properties.*

6.7 Instrument requirement

The science described in the previous sections require a variety of instruments in both the optical and infrared (near and mid) regions. The generic instruments that would be required are

- Wide field optical imager
- NIR imager (AO)
- Low resolution NIR spectrometer (AO)
- Multi-object low resolution spectrometer - optical and NIR (seeing limited, AO)
- Integral Field Unit (NIR, AO)
- High resolution spectrometer – optical and NIR
- Mid-infrared imager (AO)
- Mid-infrared low resolution spectrometer
- Spectropolarimeter – optical and NIR

The percentage-wise breakup of the instrument requirements vis-a-vis the science goals is

- ~30% of science proposals require high resolution spectrometer
- ~60-70% require imaging + low resolution spectroscopy in optical and NIR
- ~20% require wide-field imaging and/or multi-object/IFU spectroscopy
- ~5-10% require mid-IR
- <2% require polarisation

The planned suite of instruments on the TMT comprises instruments that can address almost all our requirements. The science goals and the instruments that meet the respective requirement are listed in Table 1.

Table 1. A list of our science goals and the instruments required to meet the science requirement. Also listed are the proposed instruments for TMT that meet the respective requirement.

Science Goal	**Instrument Requirements**	**TMT Instruments**
Studies of starforming regions	optical and NIR wide field imaging (seeing limited and AO), optical, NIR and mid-IR spectroscopy	Wide field optical spectrometer (WFOS), Infrared Imaging Spectrometer (IRIS), Infrared Multi-slit Spectrometer (IRMS), Wide Field Infrared Camera (WIRC), Infrared Multiobject Spectrometer (IRMOS)
Exo-planets	High resolution optical and IR spectroscopy (seeing limited and AO), high spatial resolution, AO-fed mid-IR imager	High resolution optical spectrometer (HROS), NIR echelle spectrometer (NIRES), Mid-Infrared echelle spectrometer (MIRES), Planet Formation Imager (PFI)
Stellar explosions and extreme physics	Optical and IR imagers (seeing limited and AO), optical and IR low resolution spectroscopy and spectropolarimetry	Wide field optical spectrometer (WFOS), Infrared Imaging Spectrometer (IRIS), Infrared Multi-slit Spectrometer (IRMS), Wide Field Infrared Camera (WIRC)
Galaxy formation	High resolution optical and NIR spectroscopy, IFU, NIR and mid-IR imaging	High resolution optical spectrometer (HROS), Infrared Imaging Spectrometer (IRIS), NIR echelle spectrometer (NIRES), Mid-Infrared echelle spectrometer (MIRES), Infrared Multiobject Spectrometer (IRMOS)
Stellar abundances, IGM	High resolution optical and NIR spectroscopy	High resolution optical spectrometer (HROS), NIR echelle spectrometer (NIRES)

A match of the instruments required for meeting our science goals, and those proposed for the TMT shows the absence of (a) a wide field optical imager and (b) a spectropolarimeter.

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