Bull. Astr. Soc. India (2003) **31**, 231–236

Sub-Millimeterwave Efforts in India

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Abstract. The submillimeter waveband (3 to 0.3 mm) is important for photometric and spectroscopic studies of the high redshift Universe and of the deeply embedded star forming regions in our and nearby galaxies. The upcoming Atacama Large Millimeterwave Array (ALMA) will have a large collecting area and high spatial resolution, but small field of view and correlation bandwidth. This creates both an opportunity and a need for an effective complement: a large single dish fitted with a modern photon detector array can be faster than ALMA for continuum source detection. Besides being powerful in its own right, such an instrument can also supply zero-spacing data for making more complete spectral line images with ALMA. Our natural strength in having many high altitude desert sites in the Himalayas can be leveraged to take our nascent submillimeter efforts to the frontiers of this new waveband. Building large submillimeterwave telescopes calls for unconventional approaches. In this paper, we first discuss the astronomical importance of the submillimeter waveband, then present our ongoing site survey efforts in the Himalayas and then put forth a novel way to build a large submillimeterwave antenna. Finally, we summarise our efforts so far and our plans for the near future.

Keywords : submillimeter – telescope design – high-altitude sites

1. Submillimeterwaves - A Key Complementary Waveband

The optical waveband has played a major role in shaping our knowledge of the Universe. However, it has some important limitations: (i) cold objects do not emit in the visible band; (ii) visible light suffers absorption by interstellar dust; (iii) far away objects undergo large cosmological redshift which shifts the fainter restframe ultra violet emission into the observer's visible band (K-correction). On all these counts, submillimeter waveband complements the optical: cold objects are bright in the submillimeter, interstellar dust does not affect this radiation and the K-correction

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for far away objects is negative in this band, making them more luminous! Light truly carries complementary information about the celestial objects in different wavebands. Obtaining a comprehensive view necessitates multiwavelength observations and access to sensitive telescopes in major wavebands. The submillimeter is a key waveband that will play a vital role in resolving some of the contemporary astronomy questions such as: how did *the Universe, galaxies, stars & planets, dust* and *biogenic molecules* form and evolve? Such studies have become possible now owing to the recent *progress in detector technology* and *the development of high altitude desert sites* (where lower atmospheric water vapour allows submillimeter astronomy).

1.1 A Tool to Study Cosmology & The Early Universe

Millimeter and submillimeter waves are important to study the CMBR anisotropy and its modification by the foreground matter. One can combine accurate measurements of *Sunyaev-Zeldovich effect* with high-resolution, multi-channel X-ray images of nearby and distant clusters to derive the Hubble constant in an independent way. Studies of galaxies over a large volume at high redshift is crucial to understand the early evolution of the Universe and to constrain cosmological models. The submillimeter waveband is best suited for such studies: substantial dust, present in the distant early galaxies, *in-situ* reprocesses the optical and UV radiation into the restframe far infrared which gets cosmologically redshifted to submillimeter in the observer's frame (*eg.* contrast the deep optical and 850 μm SCUBA images of Abell 370 in Ivison et al. (1998)). Current submillimeter telescopes are unable to fully exploit this fact because they become confusion limited at ~0.5 *m*Jy owing to the steep increase in source count resulting from the negative K-correction (Takeuchi *et al.*. (2001)) *i.e.,* objects over a wide redshift range appear equally bright because space dilution is nearly compensated by the increased rest-frame spectral luminosity. Statistical studies of early galaxies require the confusion limit to be reduced below 0.05 *m*Jy. This needs higher resolution and sensitivity which are the main motivations to find a way to construct a large ($\gtrsim$ 30 m) submillimeter telescope. The quasar number count also increases with redshift. Their bright, compact nuclear cores are highly variable but suffer negligible interstellar scintillation in millimeter and submillimeterwaves. Therefore, such sources facilitate probing the intervening matter via studies of molecular absorption, gravitational lensing and time variability of the lensed sources.

1.2 High redshift & Nearby Galaxies

Higher the redshift, the warmer the interstellar medium (ISM). This leads to stronger emission in the higher rotational transitions of CO, the main tracer of molecular ISM, allowing us to probe such matter to farther redshifts. The many rotational transitions of CO allow wide redshift coverage with the same band: as the lower transition leaves the band the next transition enters. Further, for the same collecting area and current technology receivers, CO can be detected to farther distances than neutral hydrogen. This allows one to study CO Tully-Fisher relation, redshift evolution of molecular ISM and the evolution of the parent galaxies to farther distances. In addition, the dominant cooling lines (eg. C II in normals (Braine & Hughes (1999)) and O I in starbursts (Unger et al. (2000))) will also get redshifted into the submillimeter band permitting the study of distant objects.

1.3 Molecular Clouds, Young Stars, Planets & Interstellar Dust

Issues such as (i) how do *Embedded Young Stellar Objects* form and evolve?; (ii) how does the *Initial Mass Function* come about? (Johnstone (2002)); (iii) do *planets* grow by *core-accretion or gravitational Instability*?; (iv) how does *interstellar dust* condense around late-type stars and how much? are nearly exclusive to the waveband from millimeterwaves to far infrared. Stars are bom inside molecular clouds and studying pre-stellar cloud cores and regions around newly formed stars require this waveband. The large number of molecular transitions (Schilke et al. (2001)) in the submillimeter band allow emission and absorption line studies and hence detailed characterisations of such regions. For example, one could determine (i) the *temperature*, from symmetric top molecules; (ii) the *density*, from excitation analysis; (iii) the *magnetic field*, from polarised dust emission and Zeeman splitting of select molecular lines; (iv) the *dynamics*, from modeling self-absorption; (v) the *kinematics*, from accurate line-center velocities; (vi) the *ionisation levels*, from ion-abundances; (vii) *Molecular evolution*, from molecular depletion; (viii) the *dust formation*, from depletion of refractory molecules in late-type stellar envelopes; (ix) the *presence of proto-Jovians*, which have luminosities of $\sim 10^{-4}$ $L_\odot$ (0.1 mJy at 0.85mm) and readily detectable upto 200*pc*, by modeling the spectral energy distribution towards young stars.

2. High Altitude Desert Sites – a Natural Asset

Few places on earth are free from man-made radio-interference. Such regions have become important for low frequency radio astronomy. Similarly, high altitude desert sites, essential for submillimeter astronomy, exist only in a few places on Earth. Significant flat spaces with altitude above 5000 m exist only in the Himalayas in the north and the Andes in the south. We could exploit this natural asset for frontline astonomical research in this newly opened, potent window.

The Indian Institute of Astrophysics (IIA) has been developing the site at Hanle, where the 2 m Himalayan Chandra Telescope operates and substantial infrastructure already exists. This site is located at $32^\circ\ 47'\ 46''N$ longitude, $78^\circ\ 57'\ 51''E$ latitude and 4500 m altitude. It is largely dry and windfree: annual precipitation of rain and snow < 10 cm and wind speeds are typically < 5 m/s and rarely reach a maximum of $\sim$ 30 m/s.

In a collaboration between the University of Tokyo, the IIA and the Raman Research Institute, a 220 GHz radiometer has been made and installed at Hanle. It has been measuring 220 GHz opacity (τ_{220}) over the past 3 years. During October to April, the measured τ_{220} goes below 0.06 for significant periods implying precipitable water vapor of less than 2 mm, suitable for submillimeter observations. The data indicates that the *winter transparency* is better or comparable to Mauna Kea with more fractional time with $\tau_{220} < 0.1$ (Ananthasubramanian, Yamamoto, &

Prabhu (2002)). Measured τ_{220} is well correlated to those predicted from the surface weather parameters (Fig.1a: *Sridharan T. K., CfA, USA*, private communication). During the months with low τ_{220}, the measurements may suffer from systematics owing to standing waves between the transparent dome and the receiver and the winter performance is likely to be better. We plan to make *Fourier Transform Spectrometer* (FTS) measurements to compare with other sites.

Recently, Sridharan (private communication) has identified another site closer to Leh near Polakongka La based on satellite images and has, in collaboration with the IIA, set up an automatic sky monitor in a hut to study the cloud cover characteristics. The GPS coordinates of the hut are: 33° 15′ 39″*N* longitude, 78° 10′ 43″*E* latitude and 5010 m altitude. In the photo (Fig.1b) taken in early winter (Dec 2002) snow is found only at altitudes $\gtrsim$ 6000 m in the nearby peaks, indicating highly dry nature of this place. *A weather station* to measure ground weather parameters will be in place soon. This will help predict τ_{220} and allow comparison with other sites. We also plan to undertake radiometer and FTS measurements at this site.

3. Making a Large Telescope

It is difficult and expensive to make large submillimeter wave telescopes with paraboloidal primaries: the requirement to move the large primary in elevation introduces gravitational distortions. Homologous designs can compensate to a certain extent but the cost to keep the overall *rms* surface error to be $\lesssim 20\,\mu m$ becomes prohibitively expensive for sizes beyond ~ 15 m, calling for unconventional designs. Paraboloids also need to be mounted on pedestals taller than the radius of the primary leading to increased cost and wind loads. The elevation movement also requires that the primary support is brought to a central hub leading to larger torques requiring stiffer backup structure and therefore increased cost. Many of these problems are avoided by making the primary static and accepting limited elevation coverage. We have been exploring spherical alternatives (Balasubramanyam (2001)) to construct a large ($\gtrsim 30\ m$) submillimeterwave dish economically. While the proposed model with an f/D of 0.5 provided acceptable elevation coverage, obtaining reasonable field of view with simple optics has been a problem. Recently, Burge & Angel (2001) have come up with a large telescope design with spherical optics for both the primary and secondary and achieve a large correctible field of view with two additional mirrors. However, their design requires that the f/D be as large as 2 and the secondary size be half that of the primary. The former means the elevation coverage will be limited to ~ 8° and the secondary has to be mounted rather high; the latter means one needs to move a relatively heavy secondary to cover this elevation.

Here, we propose a cylindrical alternative (Fig.1c) that we have been exploring for some time. This seems to avoid all the pitfalls of the spherical design while retaining its advantages and offering some of its own. The idea is simple: instead of trying to focus light in both the dimensions at the same time, we could achieve it in two steps; first, we concentrate the light in one dimension using a parabolic cylindrical primary to a smaller (say 10% of the primary width) cross section and then recollimate it to a rectangular beam using another confocal parabolic cylindrical secondary; this beam is then compressed in the orthogonal dimension using the third parabolic cylinder to a smaller square cross section; this is then brought to a point focus by a fourth surface (Fig.1d). It is important to note that, for oblique incidence of light at an angle to the axis of the cylinder, the line focus of a parabolic cylinder simply shifts laterally by the same angle in the opposite direction. This can be recollimated by a static secondary if its length is extended by $2f \times sin(\theta)$, where f is the focal length and θ is half the elevation one wishes to cover. This is ~30% for an f/D of 0.6 and an elevation coverage of $\pm$ 20°. The elevation is then covered just by rotating the tertiary (and further optics) about its center of curvature. One could use spherical optics to make the tertiary static as well. Moving the narrow tertiary is not difficult in any case. One could possibly gain larger field of view, useful for fine tracking and fast switching, by optimising the cross-sectional shapes, *á la* Ritchey-Chretien, for zero spherical and comatic aberrations. The projected primary area changes negligibly even for 20° oblique incidence, allowing elevation from 40° to 80° to be covered easily with the primary axis inclined at 30° to the horizontal. This elevation coverage is sufficient since below 40°, airmass will cripple observations and above 80°, tracking celestial objects with a large single dish is difficult. Thus, this cylindrical design has many advantages: (i) mirrors are made *economically* by bending polished sheets; (ii) the static primary *avoids* gravitational distortions; (iii) being close to the ground, wind loads are *reduced* (further reduction possible by building a wall around it); (iv) *rain or snow* easily slips off the inclined primary; (v) fixed gravity makes optimising the backup structure for reducing *thermal distortions* simpler.

4. In Summary

The submillimeter waveband is a new major window that will play a key role in resolving myriad contemporary astronomy issues. India has the advantage of *high altitude desert sites*, a rare natural asset necessary for submillimeter explorations. *Site characterisation* is underway at two sites: Hanle is possibly better than Mauna Kea and Polakongka is promising. We could leverage this natural advantage to break into the frontiers of modern submillimeter astronomy. A *large (~30 m) submillimeter telescope* is needed to beat the confusion limit. Such a telescope fitted with a large format (10×10) photon detector array can complement and compete with ALMA. *Fruitful collaboration* for such an array is possible (Matsuo et al. (2001), private communication). Such a large telescope can be constructed economically based on the *novel cylindrical design* proposed here: it will have both enough field of view and wide elevation coverage. We are constructing *a proof of concept* 4 m transit telescope to be used at a site in the Himalayas.

Acknowledgements

I thank Ananthasubramanian, P.G. (RRI) and Prabhu, T.P. (IIA) for the site details, Sridharan, T.K. (CfA) for his private communication and many a help, discussions and encouragement, and my son and wife for their great support.

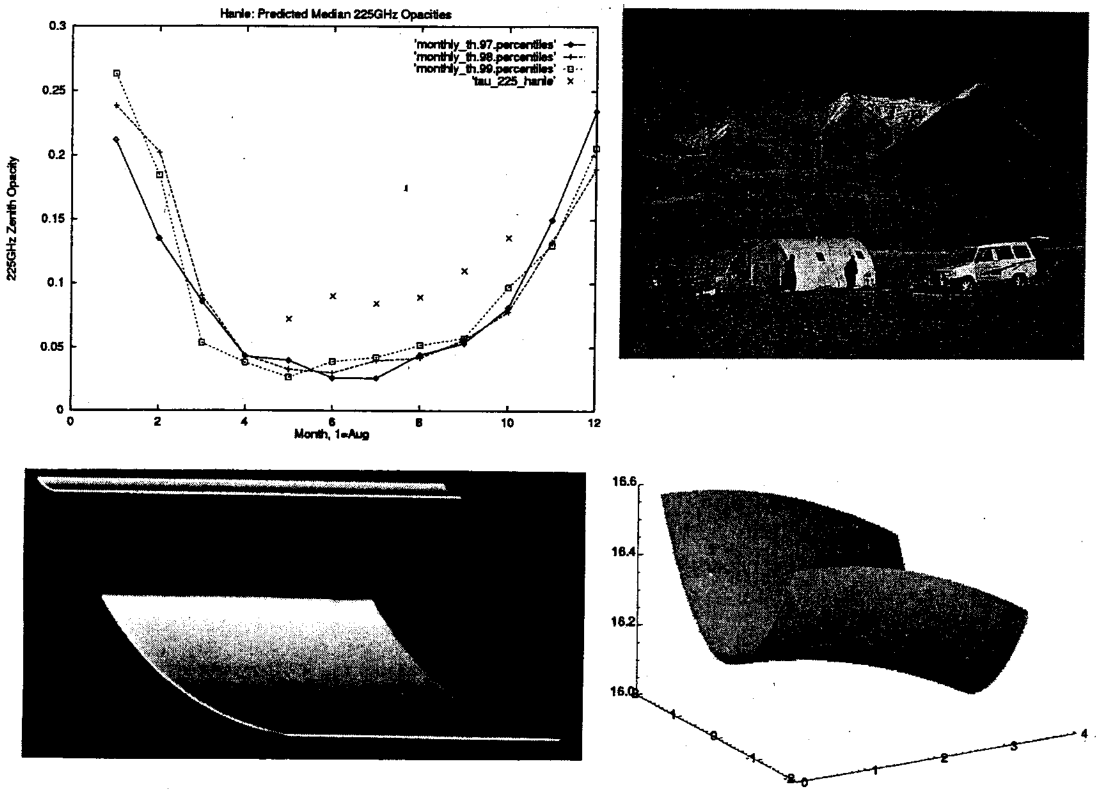

Figure 1. (a) *Top left:* Predicted *vs* measured 220 GHz opacities (Courtesy Sridharan, T.K.); (b) *Top right:* Early winter photograph of the Polakongka site; (c) *Bottom left:* A schematic of the novel cylindrical design; (d) *Bottom right:* The shape of the Quarternary

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