Bull. Astr. Soc. India (1993) **21**, 273-280

Imaging studies in the near infrared region

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Abstract. The advent of array detectors has given a tremendous boost to the detection capabilities in the near infrared region over the last 5 years. A variety of instrumentation has been and is being built around these panoramic detectors. Several important advancements have been made in the fields of star formation, stellar evolution and extragalactic astronomy. This article reviews some of the recent results on very low mass stars, circumstellar matter in AGB stars and starburst galaxies obtained using the infrared arrays. Future perspective in the Indian context is outlined.

Key words : near infrared—array delectors—AGB stars—low mass stars—starburst galaxies

1. Introduction

The recent advent of array detectors has given a tremendous fillip to the capabilities of imaging and detection in the near infrared (IR) region (1-5 μm) to tackle a variety of problems in astrophysics (e.g. Elston 1991). The main advantage comes from the fact that the pixel size in an array detector is physically smaller (≤ 40 μm) than the size of the single detector (≤ 500 μm) reducing therefore the noise by more than a hundred times. In the recent years a number of observational programmes have been launched by groups all over the world making use of the now commercially available array detectors. Here in this review we report the recent results in some realms of astrophysics obtained elsewhere. In section 2 we discuss the currently available IR arrays and their characteristic features; in section 3.1 we present some results on the high spatial resolution observations made recently on AGB stars; in section 3.2 recent observations on starburst galaxies are discussed; section 3.3 deals with the attempts to detect the ever-eluding brown dwarfs; and in section 4 we conclude by listing out the priorities for our own programmes of observations using the array detectors in future.

2. Infrared array detectors

The currently available IR detectors are of two categories : (i) Indium-Antimonide (In-Sb) arrays for 1-5 μm range and (ii) Mercury-Cadmium-Telluride (Hg-Cd-Te) arrays for 1-2.5 μm range. The former is currently available in 128 × 128 format with pixel sizes of 40μm and the latter is available in 256 × 256 format with around the same pixel sizes. The In-Sb arrays reach optimum performance at temperatures of ~ 50K with quantum efficiency of ≥ 0.6 in the K-band, while the Hg-Cd-Te arrays work at the liquid nitrogen temperatures (77K) with quantum efficiency ≥ 0.7. All these detectors operate in the photo-voltaic mode. In addition to these two more popular arrays, Gatley *et al.* (1991) have discussed the use of a 256 × 256 Platinum Silicide (Pt-Si) array. Detailed technical discussions on the 2-D detectors can be found in Wynn-Williams & Becklin (1987), Blessinger *et al.* (1990, 1991) and Moorwood & Finger (1992).

Due mainly to the dramatic reduction in the background noise and a substantial improvement in the image wandering as compared to a single detector, it is possible to achieve background-limited performance in the case of the 2-D array detectors with quantum efficiencies as high as 0.7. It was estimated by Rayner *et al.* (1991) that a limiting magnitude of 18 could be achieved with 3σ uncertainty in 5 mt of integration on an 88 inch telescope. Table 1 gives limiting magnitudes for typical single (1-D) and array (2-D) detectors operating at 1.2 m and 2.3 m telescopes for two values of signal to noise ratio (SNR).

Table 1. Limiting magnitudes for 1-D and 2-D detectors

Aperture (m)	1.22		2.34	
Detector	1-D	2-D	1-D	2-D
SNR=50	3.1	2.6	4.6	10.8
SNR=10	5.1	11.6	6.5	12.8

There has been a variety of instrumentation based on these detectors, covering all aspects: imaging photometry (Bushouse 1987; Capps *et al.* 1989), imaging polarimetry (Minchin *et al.*, 1991), medium-resolution spectroscopy using gratings (Moorwood 1987) and Fabry-Perot etalons (Fischer *et al.* 1991; Krabbe *et al.* 1991) and high-spatial resolution instruments like speckle interferometry (McCarthy *et al.* 1991; Marriotti & Perrier 1991) and lunar occulations (Richichi 1989). A comparison of the high-spatial resolution techniques has been made by Beuzit *et al.* (1991) which we have summarized in table 2. Limiting magnitude differences are listed for different angular separations of binary stars. Bascially the speckle technique can resolve better only if the magnitude differences are within about 4 magnitudes, while imaging with the coronagraphic mask is capable of reaching differences of as large as 8 or 9 magnitudes. The seeing-limited imaging is good only in cases where the separations are larger than one second of arc.

Table 2. Binary star magnitude differences for imaging

Separation	Speckle	Seeing-Limited	Coronagraphic
3 arcsec	3.8	6.3	9.4
2 arcsec	3.8	3.8	8.9
1 arcsec	3.8	limit	8.2
0.3 arcsec	3.8	—	limit
0.2 arcsec	3.8	—	—
0.1 arcsec	limit	—	—

The near IR region basically comprises of a few windows that are spared of the absorption by the constituent moleculesof the earth's lower atmosphere. A number of important spectral lines from molecular, atomic and ionic species occur in these windows by studying which the physical conditions prevalent in various astrophysical objects can be investigated. Table 3 summarizes the atmospheric windows and some of the important spectral lines:

Table 3. Atmospheric windows and spectral lines in the near infrared

Photometric windows		Spectral lines	
Band	λ in μm	Line	λ in μm
J	1.25	[FeII]	1.257
H	1.65	[FeII]	1.644
K	2.20	[SiVI] (i.p.=167 ev)	1.96
		HeI	2.06
		H_2 v=1-0S(1)	2.122
		H Brγ	2.166
		CO v=4-3	2.365
		[SiVII] (i.p.=205 ev)	2.48
L	3.50		
M	4.80	H Brα	4.051
N	10.0		

The physical mechanisms responsible for the excitation of these lines are important in order to understand the energetics of the astrophysical objects. For instance the vibrationally excited molecular hydrogen lines can in principle be caused by either a thermal process involving shock-excitation or by a non-thermal process such as flourescence by uv or x-rays. These different mechanisms will populate different levels differently and hence the line ratios will decisively tell the excitation mechanism.

3. Astrophysical problems

There are a number of astrophysical problems which are now being tackled with a renewed vigor thanks to the advent of the near IR arrays. Practically, from objects next door in our solar system like comets and planetary atmospheres to those in the farthest frontiers of the Universe like AGNs and high-redshift radio galaxies require inputs in this important spectral band. There has been an explosion of observational activity in various fields in the past couple of years (Elston 1991, for a comprehensive compilation). We shall discuss in brief only a few problems here in this review.

3.1. *Circumstellar matter in AGB stars*

AGB stars are stars of intermediate mass (2-8 $M_\odot$) evolving beyond He-burning having C-O cores and climbing the H-R diagram a second time asymptotically. These stars, which undergo pulsations leading to their variability (long-period or Mira variables), are supposed to evolve into planetary nebulae (PN) stage with the C-O cores becoming degenerate and cooling off as white dwarfs. Beyond the AGB stage the stars undergo a considerable mass loss (Anandarao *et al.* 1993) and are eventually enshrouded by dust shells becoming opaque to visible radiation. This stage known as the OH-IR stage (owing to the detection of OH maser lines and the fact that the stars emit mostly in the near IR) is very crucial as immediately after this stage the stars shed their outer envelopes in a much more enhanced mass loss process leading to PN (Pottasch 1984). It is this stage in the evolution of the intermediate mass stars that is not understood clearly. The crucial questions are (i) what are the mechanisms of mass loss and (ii) what is the geometrical shape of this mass loss. The first question is important in order to know the amount of the mass lost and therefore reconcile with the observed mass in the PN or in circumstellar matter in AGB stars. The second one is crucial to decide the ultimate morphology of PN. A spherically symmetric mass loss would yield spheroidal morphology while an axially symmetric mass loss would yield bipolar morphology. One more important question is whether the mass loss is episodic in the sense that different shells are ejected at different epochs yielding perhaps the multiple-shell PN. Some evidence for the presence of multiple shells was shown by way of a model for the IRAS data in the case of the peculiar symbiotic system R Aquarii (a Mira variable and a white dwarf) by Anandarao & Pottasch (1986). Their prediction on the size of the inner shell was later confirmed by the HST results (Burgarella *et al.* 1992) and by the L-band two-dimensional speckle interferometry by Tessier *et al.* (1991). One of the most spectacular and crucial observation has come from the two-dimensional speckle interferometry in H, K and L bands in the carbon-rich Mira variable IRC + 10216 in which the circumstellar shell has been shown to be axisymmetric (Christou *et al.* 1991). Furthermore, the direct IR imaging of the bipolar PN NGC 6853 (the Dumbbell nebula) has resolved a companion for the central star (Zuckerman *et al.* 1991). This result implies perhaps that the binary central stars could distort the circumstellar matter to produce bipolar morphologies.

It is also important to detect and delineate the photodissociation region in the outer regions of the PN shells from the observations of ions whose ionization potentials (i.p.) are smaller than that for the hydrogen atom and comparing such a map with that of molecular hydrogen emission. The most suitable ion for this purpose is the singly ionized sulphur whose i.p. is 10.3 ev. One more important problem that needs attention is the interaction of the nebular shells with the interstellar medium (ISM) which will eventually help deriving the physical parameters of the ISM.

3.2. *Starburst galaxies and AGNs*

Starburst galaxies are spiral galaxies having large IR luminosities (ultraluminous) compared to the normal galaxies. In a majority of the cases the starburst activity is associated with the interacting or merging galaxies. The large IR luminosities can either be due to reradiation from the heated dust or to the accretion on to the central compact source (AGN). It is therefore important to find out the extent of the starburst activity in order to understand the energetics of the observed luminosities. For instance, the luminosity of 10^{10} $L_\odot$ requires the dust of temperature 300K at a radial distance of 3pc from the heating source at the centre. This distance is so small that it is impossible to resolve it at the distances of the external galaxies and obviously the observation on the extent of the starburst activity would help in assessing the dust contribution to the IR luminosities.

Near IR imaging would reveal the structure that the optical images cannot be due to the obscuration by the dust especially in the nuclear regions where enhanced bursts of star formation are going on. For instance, the recent observation of the so-called hot-spot galaxy, NGC 2903 revealed distinct clumpy structure in the near IR images as compared to those in the optical suggesting that the star formation has the clumpy structure (Sharp & De Poy, 1991). Observations on a number of starburst galaxies by Bushouse (1991) and Stanford & Bushouse (1991) revealed vast differences with the optical images especially in the small-scale structure. Circumnuclear starburst activity has been detected by Rouan *et al.* (1991) in their K band images of most of the Seyfert galaxies (6 out of 7) and ultraluminous galaxies in a structure that resembles a ring. This circumnuclear ring-like structure has also been identified in the barred spiral galaxy NGC 4321 in Hα line by Arsenault *et al.* (1988) using an imaging Fabry-Perot interferometer.

On the spectroscopic side it is important to observe the emission line images in the molecular hydrogen, [FeII] lines and the high-excitation coronal lines of [SiVI] and [SiVII]. The H_2 line emission can be caused by the thermal excitation of vibrational levels in the regions of star-formation, colliding disks and the nuclear activity due to shocks. Fischer *et al.* (1991) have attempted to assess the relative contribution of these three agents from the spectroscopic imaging (using a Fabry-Perot interferometer) of the H_2 v = 1-0 S(1) line at 2.122 μm and the Brγ recombination line of atomic hydrogen and the neighbouring continuum of the central region. The [FeII] lines are identified with the supernovae remnants and hence are rather directly correlated with the star formation activity (Kawara *et al.* 1988; Moorwood & Oliva 1988) as the shock fronts from the supernovae are thought to be the primary cause for the gravitational instability. The [FeII] lines can thus be used to distinguish between the starburst and AGN phenomena. The high-excitation coronal lines of [SiVI] and [SiVII] have already been identified in PN and novae. These lines have for the first timebeen identified in the seyfert galaxy NGC 1068 by Moorwood & Oliva (1991) with widths broader than the other low excitation forbidden lines implying possibly that these coronal lines occur in regions of high densities alongside the permitted recombination lines.

3.3. *The search for brown dwarf*

Brown dwarfs (BD) (see Burrows *et al.* 1989) are supposed to be objects which are not massive enough to burn the core hydrogen. The critical mass below which this happens is theoretically estimated to be ~0.08 $M_\odot$. The stellar surface attains a temperature of ≤ 3000K, powered mainly by the gravitational energy. A brief (~10^6 years) phase of core deuterium burning has been suggested but does not really change the ultimate destiny of these stars. These failed stars emit mostly in the near IR region. The significance of the search for the BDs lies in the possibility that they can contribute substantially to the missing or the dark matter in the galaxies (Adams & Walker 1990). Also the initial mass function (IMF) in the low mass end is not known observationally (Burrows *et al.* 1989).

The best places to look for the BD are (i) as companions in the nearby late-type dwarfs and (ii) as field objects in the open clusters. In all these studies one needs to assume that the IMF for the binaries is the same as that for the field stars. Earlier observations were done using the speckle interferometry in one dimension. The claims of McCarthy *et al.* (1985) on the possible detection of a companion (VB8B with an estimated mass of ~0.1 $M_\odot$) for the M dwarf star VB8 were later on disputed by Perrier & Mariotti (1987) and Skrutskie *et al.* (1987). Now, with the advent of 2-D detectors it has become possible to continue the search for BD in a much more cohesive way than before. The searches conducted by Skrutskie and his colleagues (Skrutskie 1991) in several closeby open clusters like Pleiades, Hyades and Taurus in comparison with the solar neighbourhood yielded just a handful of low mass stars proving perhaps that the IMF may not rise substantially in the low-mass end. D'Antona & Mazzitelli (1985) derived a mass function of the type $\phi(M) = M^{-0.7}$ for the solar neighborhood for masses up to ~0.2 $M_{\odot}$. Assuming the same mass function Skrutskie (1991) reaches the possible inevitable conclusion that the BD may not be significant to explain the dark matter in the galaxies. The main problem in the detection of BD comes from the fact thatthe old BD are too faint to be detected with absolute magnitudes fainter than 16 mag posing a sensitivity problem for the detectors while very young BD though as bright as 5-10 mag do not distinctly distinguish themselves out from their low-mass counterparts leaving always an uncertainty that the suspected BD could as well be a low-mass star as borne out in the theoretical models of Nelson *et al.* (1986). Perhaps very large arrays with higher sensitivities in the future may revive the problem of detection of BD but as of now it appears that the BD is still an eluding enigma and a formidable challenge in observational astronomy. Further, there have been attempts to detect some molecular bands from the BD (Stauffer *et al.* 1991) for the candidates identified by Forrest *et al.* (1988) in Taurus and concluded that none had the spectra consistent with the low effective temperature expected in these objects. It has very recently been suggested (Robolo *et al.* 1992) that lithium resonance lines could be used as a spectroscopic discriminant between very low mass stars and BD close to the substellar mass limit, for, the cores of the low mass stars are hot enough to burn and deplete lithium while it should be preserved in BD with masses below 0.6 $M_{\odot}$.

4. Future perspective in the Indian context and conclusions

In what preceded we have attempted to describe some of the exciting results which have come about in the very recent years using the IR arrays. It appears to offer a more exciting future ahead of us and with the facilities that are at our disposal it may be worthwhile identifying the possible areas in which a significant contribution can be made in our country. In some of these areas there exist already programmes that are being carried out using imaging detectors in the visible region. With the available largest telescope in the country, namely, the 2.34 m Vainu Bappu telescope (VBT) and with arrays that are available commercially, the following scientific programmes appear to be the most viable :

1. IR photometric and polarimetric imaging of the nearby star forming regions in order to identify the cocoon stars and to determine the IMF of the low-mass stars.
2. Imaging the circumstellar envelopes in the IR especially for AGB stars to find out the morphology and the geometry of the circumstellar shells using the IR speckle technique complimented by the lunar occulation observations where possible.
3. Spectroscopic imaging of planetary nebulae to delineate the photo dissociation regions and to find out the physical parameters of the ISM from the study of the interaction of the nebular shells with the ISM.
4. Spectroscopy, photometry and polarimetry of the starburst galaxies to find out the extent of starburst activity to decide whether the IR luminosity is due to dust or the central compact source and thus to demarcate between the AGNs and the starburst galaxies.

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