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Near-infrared photometric and spectroscopic studies on star forming regions

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Abstract. We have initiated a programme to study near-infrared photometry and spectroscopy of low and high mass star forming regions and young stellar objects using the HgCdTe 256×256 array camera/spectrograph at the 1.2 m telescope. We describe here some of the significant results obtained under this programme on (i) a low mass T Tauri type pre-main sequence(PMS) star; (ii) an intermediate mass star forming region; and (iii) two high mass star forming regions.

Keywords : Star Formation, YSOs, Pre-main sequence stars, Molecular Hydrogen, Outflows, Accretion disks

1. Introduction

In spite of decades of research, there are a number of unsolved problems related star formation phenomena. With the advent of infrared and mm wave techniques a lot of progress has been made in the recent decade. Currently one broadly understands the processes of low mass star formation, thanks to a number of important observations(e.g., Najita 2000 and the references therein); but there are not many observations on the high/intermediate mass star formation mainly due to their large distances, large extinction that they suffer due to the presence of parent molecular cloud and a very short pre-main sequence life time as compared to the low mass counterparts(for a recent review, Churchwell 2000). The main issues are the mechanisms of formation of high mass stars: whether by accretion (like low mass stars) or by coalescence. This may have a bearing on the observational fact that massive stars always form in clusters while low mass stars form in isolated environments.

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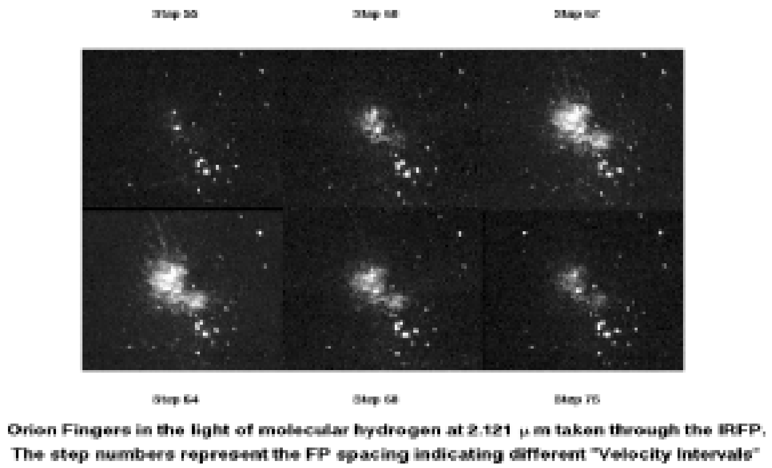

Figure 1. Molecular Hydrogen S(1)1-0 line at 2.121 μm scanned by the NIFS. One can see the emission in the line peaking in the step 64 (details in Anandarao et al., 2000).

Also it is believed that high mass pre-main sequence(PMS) stars too undergo phenomena of outflows and accretion disk formation - which supports the accretion mechanism. With the acquisition by PRL of the near-infrared camera/spectrograph (NICMOS3), we got an opportunity to initiate a reasonably competitive scientific programme on star formation studies. With this aim, we had taken up a near-infrared observational project to investigate the regions of low/intermediate/high mass star formation using the Mt Abu 1.2 m infrared telescope with the NICMOS3 camera. Recently we built a near-infrared Fabry-Perot imaging system that works in tandem with the NICMOS3 camera in order to take very narrow-band images of extended sources such as star forming regions in emission lines notably, molecular hydrogen vibrational-rotational lines and atomic hydrogen recombination lines(Anandarao et al., 2000). Fig 1 shows molecular hydrogen images in Orion trapezium region taken with the Near-infrared Imaging Fabry-Perot Spectrometer(NIFS). Here in this article we present some significant results obtained so far under this project. These results include observations made elsewhere also in addition to those made at Mt Abu.

2. Molecular hydrogen jets in RNO 91

RNO91 is one of the only two known PMS stars in the L43 dark cloud in Ophiucus. It was classified as an M0.5 type T Tauri star. Weintraub et al., (1994) showed from K-band polarimetric images and 3-5 μm spectra that RNO 91 is surrounded by a disk-like structure of radius 1700 AU comprising frozen H_2O and CO. Bence et al., (1998) detected at millimeter wavelengths a CO outflow that has spatially separated red- and blue-shifted lobes. Thus, RNO91 is a unique disk+outflow system. The aim of our study was to detect molecular hydrogen outflow in this object.

Molecular hydrogen is the most abundant molecule in the interstellar medium and its spectral signatures in the near-infrared are recognized as powerful tools to study the star-forming regions (Shull and Beckwith 1989). As it is a homonuclear molecule it does not have a permanent dipole moment and hence the pure rotational and vibrational-rotational dipole transitions are not permitted. But the weak and slow electric quadrupole transitions are possible by radiative excitation to the first and second electronic states ($B^1\Sigma_u$ and $C^1\Pi_u$, Lyman and Werner states) at excitation energies of $\sim$ 11.4 and 12.2 ev respectively, followed by radiative decay to the ground electronic state($X^1\Sigma_g$). In about 10% of the cases these transitions lead to dissociation of the molecule and the majority will cascade through several vibrational rotational transitions(Shull and Beckwith 1989). The excitation of the quadrupole transitions in molecular hydrogen involve mainly two competing processes: (i) shock heating and (ii) UV fluorescence (Burton 1992). It is possible to distinguish between these two processes by measuring the ratios of intensities of lines arising from two different vibrational levels (Sternberg and Dalgarno 1989).

Near infrared spectroscopic observations were made on March 25, 1998 at Gurushikhar 1.2 m Infrared Telescope using the NICMOS3. In addition to this, narrow band images in H_2 1-0 S(1)(2.122 μm), Brγ (2.165μm) and continuum (2.104μ m) filters were obtained by the United Kingdom Infrared Telescope (UKIRT) Service Observing Program on 8 September, 1998, using the near-infrared camera, IRCAM3.

The infrared spectrum of RNO91 shows emission of molecular hydrogen from an outflow in the N-S direction and from a spatially unresolved region close to RNO91(see Fig 2A). We estimate a mass flow rate of M = 4 x 10^{-8} $M_\odot$ /yr. from this spatially unresolved region around RNO 91. The line fluxes yield net warm H_2 mass of $\sim$ 5 x 10^{-4} $M_\odot$. The asymmetric outflow seen here in H_2 emission, extending roughly N-S, appears to support the tilted disk and outflow model. Our narrow band images also support this scenario (Nandakumar, Anandarao and Davis 1999). From the ratio of the H_2 lines we inferred that the excitation mechanism is shock heating.

3. Clustered star formation in L1340

Small dark clouds usually have a low density of young stellar objects (YSOs) and hence are useful for investigating star formation efficiency and the time evolution of the star formation process in different parts of the clouds. With the advent of panoramic detectors, such clouds can be mapped in the optical, and together with the data in the near-infrared and millimeter wavelengths, such maps can often yield a global picture of star formation within the cloud. L1340 is a star-forming cloud in Cassiopeia, situated at a distance of 600 pc (Kun et al., 1994). The cloud hosts three red and nebulous objects RNO 7, 8, and 9 that have intense molecular emission in the ^{13}CO lines (Yonekura et al., 1997). Kun et al., (1994) identified three dense cores that are associated with the three RNOs from detailed maps of the cloud in ^{13}CO and C^{18}O. The entire L1340 cloud hosts 22 IRAS point sources that are characterized as YSOs.

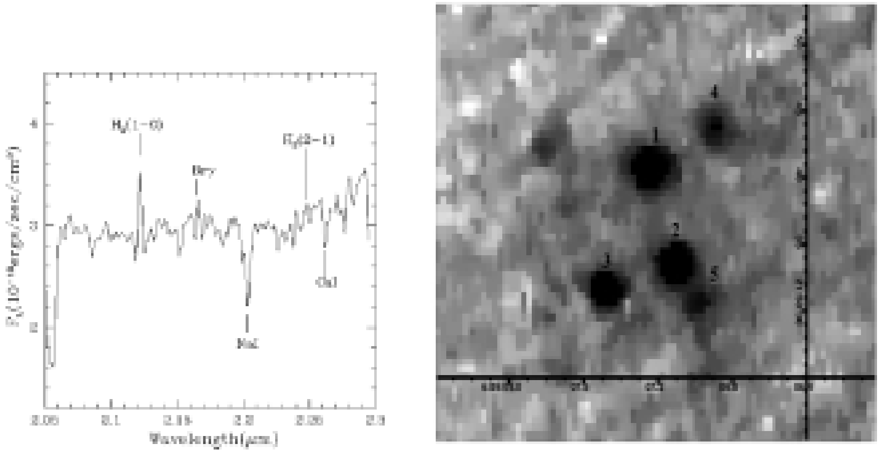

Figure 2. A(Left): Integrated K band spectrum covering an area on source of 2" in the E-W and 9" in N-S directions. The slit was kept along N-S. One can see the molecular hydrogen S(1)1-0 line at 2.121 μm and the photospheric lines of NaI and CaI. The nearly-absent S(1)2-1 line gives a clear indication that the excitation of H_2 is by shock heating (from Nandakumar, Anandarao and Davis 1999). B(Right): K' band image (2'x2' with plate scale of 0.5"/px) of IRAS 06061+2151 taken at Mt. Abu Observatory. The numbers represent the cluster of sources around IRAS 06061+2151 region The abscissa and ordinate are in J2000.0 epoch(from Anandarao et al., 2004).

We made optical imaging observations in Hα, [S II], and Gunn z filters using a CCD Mosaic (8kx8k) on the 0.9 m telescope at Kitt Peak National Observatory. These images covered the entire L1340 region and are intended for searching for Herbig-Haro(HH) outflows in the region which are regarded as signatures of young stellar objects. The near-infrared K' band images of the three core regions were obtained with NICMOS3 at the 1.2 m telescope at Mt. Abu.

Our observations showed that L1340 is an active star-forming cloud with three seemingly independent cores that host various stages of low and intermediate mass star formation. Three HH flows (HH 487, 488, 489) were detected in the southwestern part of the cloud (core A/RNO 7). Two of these flows are traced back to IRAS point sources that appear to be YSOs. We also showed for the first time that RNO 7 is a Herbig Be cluster of nearly 26 stars associated with core A; the most massive member being of B5-7 spectral type. It is believed that stars later than B7 type do not form in clusters (Testi, Palla and Natta 1999). The size of the cluster ($\sim$ 0.25 pc) is nearly the same as that of the NH_3 cores detected elsewhere in the cloud (Kun et al., 2003; Nandakumar, Anandarao and Yu 2002).

4. A massive YSO in the region IRAS 05361+3539

The IRAS source IRAS 05361+3539 is identified as a massive star forming region, situated at a kinematic distance of 1.8 kpc. The integrated far-infrared fluxes(from IRAS) correspond to a B2.5 central star (of mass ~ 7 $M_\odot$). Shepherd and Churchwell (1996) found bipolar flows from the ^{12}CO velocity maps and estimated the outflow mass to be 32 $M_\odot$. We made a near-infrared study on this source to understand the star formation in its neighbourhood.

The IRAS source was observed in J, H and K' bands from Mt. Abu, using NICMOS3 on 10 January 2000, and in narrow band filters centered on 2.12 μm (H_2 1-0S(1)), 2.16 μm (Brγ), and 2.14 μm (continuum) on 25 February 2000. The J,H and Ks magnitudes of stars within a radial distance of 8' from the IRAS source were obtained from the 2MASS point source catalogue. The 2MASS observations were dated 3 February 1998. The 2MASS data were used for making J-H vs H-Ks colour-colour diagram(Chakraborty et al., 2000). Stars that show colour excess in this diagram may be identified as PMS objects (e.g., Lada and Adams 1992).

The parent molecular cloud seems to be an active star forming region as may be inferred from a number of PMS sources detected in the colour-colour diagram: a total of 6 prospective Class I sources(earliest observable phase of a PMS star with continuum emission peaking in far-infrared), including IRAS 05361+3539; and a number of faint Class II sources (Class II sources are usually signified by outflows and disks with the emission peaking in NIR) are detected in the region. One of the Class I sources detected close to IRS1 shows extreme reddening in the colour-colour plot. This YSO appears to be fainter by 1.1 magnitude in both H and K' bands in the Mt. Abu images than in the 2MASS data. The time difference between the two observations is nearly two years. Therefore, this YSO could be a variable proto-star of the FU Orionis(FUors) type. FUors are low mass PMS stars that display photometric variability possibly due to material infall from the disk. From the spectral energy distribution in the infrared region, we proposed the possibility of an accretion disk with dust temperatures 80-800 K and with an extent of several hundreds of AU (Chakraborty et al., 2000).

5. Molecular hydrogen outflows in massive star forming region IRAS 06061+2151

IRAS 06061+2151 is one of the most luminous IRAS sources believed to be associated with the galactic massive star forming region Gemini OB1 which is at a distance of 2 kpc (Carpenter et al., 1995). The CO survey of Shepherd and Churchwell (1996) categorized this object as having a moderate velocity gas flow. This Ultra Compact HII (UCHII) region was previously studied by Carpenter et al., (1995) and very recently in a near-infrared survey on UCHII regions by Hanson et al.,(2002). We had made new near-infrared photometric and spectroscopic observations of this object to investigate the nature of the PMS stars (Anandarao et al., 2004).

The J, H, K' photometric observations were made using NICMOS3 at the 1.2 m Infrared Telescope, Mt. Abu. We obtained spectra (R = 1000, 1.4 to 2.4 μm) of the brightest source (Star No. 1) in the cluster of IRAS 06061+2151 using the Near Infrared Camera Spectrometer at the 3.58m Telescopio Nizionale Galileo(TNG) at La Palma. Spectra were also obtained in a region 5" west of Star No. 1, in order to sample the nebular regions. We also obtained from TNG, images of the source in two narrow-band filters centered on 2.12 μm for the H_2 1-0 S(1) line and 2.16 μm for the Brγ line (Anandarao et al., 2004).

From our results, it appears that IRAS 06061+2151 is a cluster of at least 5 bright sources, four of which seem to be early B-type YSOs(see Fig 2B). From the J - H/H - Ks colour-colour diagram we found that one of them, S1, could be the most massive member of the cluster and S4 is a Class I type star. S3 seems to be a Class II source while S2 is likely to be Class I. The IRAS source is also associated with a nebulosity. As many as 3-4 Class I and 13-14 Class II/III sources were found in the region of IRAS 06061+2151. A new source, S5 that shows a very steep infrared energy distribution is likely a massive proto-star and its colours (lower limits) suggest a heavily embedded source.

From the narrow band image in H_2, we have detected two knot-like structures (in SE and NW directions) flanking the proto-stellar source S4 which are separated by about 0.5 pc. These knots are absent in the narrow band image in HI Brγ. The knots are likely generated by jets from S4 and are the infrared counterparts of the classical HH objects in the optical region. From our K band spectra the ratios of H_2 lines indicate that the excitation mechanism is shock heating rather than fluorescence (Black and van Dishoeck 1987; Draine and Bertoldi 1996). From these two observations, we then concluded that the region is probably pervaded by a mild shock or a photodissociation region that can excite H_2 lines but not strong enough to excite the HI Brγ line (for details, Anandarao et al., 2004).

6. Conclusions

Near-infrared photometry, narrowband imaging and spectroscopy combined with observations in the far-infrared (IRAS) and radio regions (for obtaining the density and extent of HII regions) prove to be very useful in studying the star forming regions. The jets and accretion disks observed directly or indirectly suggest that the massive stars too may be formed by accretion rather than coalescence. More observations are being planned in the future.

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