Bull. Astr. Soc. India (2002) 30, 631–636

Near-Infrared Investigations of Star Forming Regions

B.G. Anandarao*
Physical Research Laboratory, Ahmedabad-380 009

Abstract. We have initiated an observational programme on star formation using the 256×256 HgCdTe Infrared Array Camera(NICMOS3) at the 1.2 m IR telescope in Mt. Abu. The observations, being made in the spectral region 1-2.5 μm, involve broad/narrow band imaging photometry of selected small molecular clouds and medium resolution spectroscopy (with the grating spectrograph of NICMOS 3) of some bright young stellar objects. We have also developed a medium resolution Fabry-Perot Imaging Spectrometer for mapping of regions of emission in a selected emission line. We report here some of the recent results obtained by our group.

Keywords : stars:formation – Herbig-Haro Flows – near-infrared – H_2 emission

1. Introduction

One of the most fundamental problems in astrophysics that still remains to be solved is star formation. Although one broadly comprehends the major processes responsible for formation of stars, there exists a number of nagging questions that need to be addressed. For instance, we do not have clear answers to the question as to why massive stars tend to form in clusters while low mass stars form either in association with massive stars or in isolation, how the phases of mass accretion and mass outflow differ in low and high mass stars. Some of these questions can be addressed through near-infrared observations. These observations provide important inputs for understanding the processes resonsible for the evolution from the clumps in the giant molecular clouds which are observable only in mm and sub-mm waves to the more evolved individual Class I and Class II protostellear objects which exhibit accretion disks, outflows and cause Herbig-Haro (HH) objects (e.g. Andre et al. 1990).

*e-mail:anand@prl.ernet.in

Basically the difference between the high and low mass star formation can be understood by considerting two fundamental time scales (e.g. Lada 1991). The first is the free-fall time (τ_{ff}) for a cloud core to collapse under its own gravity. Mainly a function of the mass density of the core, the τ_{ff} could be considered as independent of the final protostellar mass and is given by $\tau_{ff} = \sqrt{3\pi/32G\rho} = a\ few \times 10^5$ yrs, for a typical average particle number density of $\sim 10^4/\mathrm{cm}^3$. Once the collapse gives rise to a high density stellar mass M_*, then the Kelvin-Helmholtz contraction phase commences, during which the stellar luminosity is chiefly due to the expending of the gravitational energy before the cloud reaches the hydrogen burning stage (or Zero Age Main Sequence, ZAMS). The duration of this phase depends strongly on protostellar mass and is called the Kelvin-Helmholtz time scale, $\tau_{K-H} \sim GM_*^2/R_*L_*$. For a high mass star of $M_* = 50\ M_\odot$, $\tau_{K-H} \sim 10^4$ yrs; while for a low mass star of $M_* = 1\ M_\odot$, τ_{K-H} = a few $\times\ 10^7$ yrs. Hence for a high mass star, $\tau_{K-H} \leq \tau_{ff}$, indicating that it reaches the ZAMS stage before the cessation of infall; while for a low mass star, $\tau_{K-H} \geq \tau_{ff}$, meaning that it has an observable pre-main sequence phase. It is now believed that during the pre-main sequence (PMS) stage (however short it may be for high-mass stars), all stars exhibit phenomena such as accretion disks and outflows. The high mass stars are difficult to study due to their relatively short PMS phase.

Here in this article we give three specific examples from our observations made during the last 2-3 years at Mt. Abu and other facilities elsewhere. The first one is the case of an isolated low mass star called RNO 91; the second example is on the study of a small dark molecular cloud called L1340 which is believed to be a cocoon for intermediate star formation; and the third case is that of a massive young stellar object (YSO), called IRAS 05361+3539, and its environment.

2. Detection of Molecular Outflow in the T Tauri Star RNO 91

The near-IR molecular hydrogen emission lines are considered to be important tools in studies of star formation (Shull & Beckwith 1989). The excitation of these electronic quadrupole transitions involves 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 & Dalgarno 1989). RNO91 is one of the only two known PMS stars in the L43 dark cloud in Ophiuchus. It was classified as an M0.5 type T Tauri star. An outflow driven by this star was identified at millimeter wavelengths and shown to have spatially separated red-shifted and blue-shifted lobes (Bence et al. 1998). 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, CO and possibly XCN. RNO91 is thus a unique disk/outflow system.

Near infrared spectroscopic observations were made on March 25, 1998 at Gurushikhar 1.2 m Infrared Telescope using a near Infrared Camera/Grating Spectrometer based on a

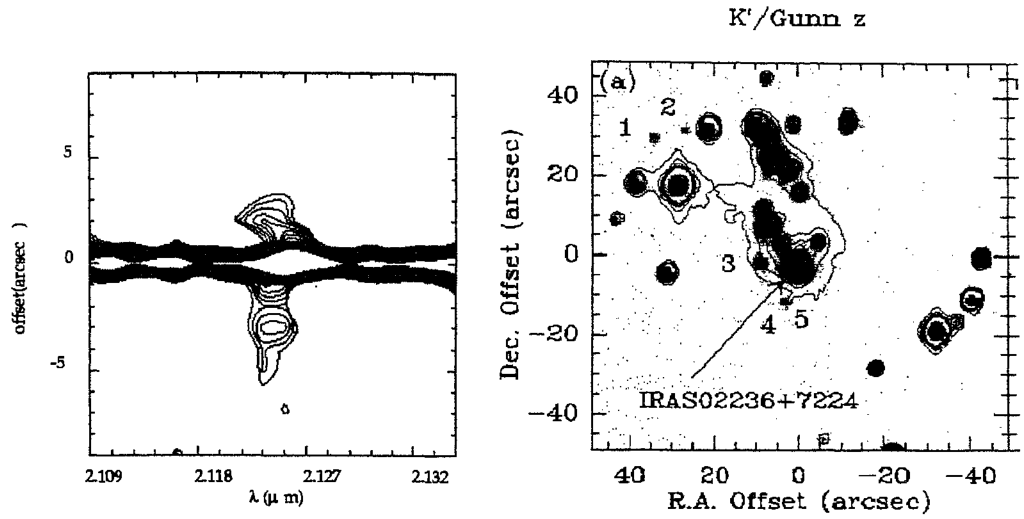

Figure 1. A(Left). Contours of H_2 2.122 μm line from RNO91 spectrum showing the extended asymmetric emission in the N-S from the center that indicates the tilt of the outflow axis. B(Right). K' image of RNO 7 overlaid with Gunn z filter contours.

HgCdTe 256 × 256 focal plane array (NICMOS3, for details of the instrument, Anandarao 1998; Nandakumar 1999). Narrow band images in H_2 ($\lambda = 2.122\ \mu$m), Brγ(λ=2.165 μm) and continuum ($\lambda = 2.104\mu$m) filters were obtained by the United Kingdom Infrared Telescope (UKIRT) Service Observing Program on 8 September, 1998, using the near-infrared imager, IRCAM3.

The infrared spectrum of RNO91 shows (Fig 1 Left) emission of shocked molecular hydrogen from an outflow in the N-S direction and from a spatially unresolved region close to RNO91. We estimate a mass flow rate of $\dot{M} = 4 \times 10^{-8}$ $M_\odot$ yr^{-1} from this spatially unresolved region around RNO 91. The line fluxes yield net warm H_2 mass of $\sim 5 \times 10^{-4}$ $M_\odot$. The asymmetric outflow seen here in H_2 emission, extending roughly N-S, appears to support the tilted disk + outflow model. Our narrow band images also support this scenario(Nandakumar, Anandarao & Davis 1999).

3. Star Formation Activity in the L1340 Dark Cloud

Small dark clouds and Bok globules are laboratories for investigating star formation phenomena. They have low densities 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 a cloud. 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 ($\sim 1^o \times 1^o$ on the sky) in Cassiopeia, situated at a distance of 600 pc (Kun et al 1994). The cloud hosts several interesting nebular features, of which three RNO 7, RNO 8, and RNO 9 have intense molecular emission in the ^{13}CO lines (Yonekura et al 1997). Kun et al (1994) presented detailed maps of the cloud in ^{13}CO and C^{18}O. They identify three dense cores that are associated with the three RNOs. The C^{18}O countours trace the dark regions of the cloud that indicate dense gas, while C^{13}O traces the brighter regions, indicating warm and tenuous gas. RNO7 is associated with core A that has a mass of 420 $M_\odot$ and an extent of 2.8×1.2 pc^2. RNO8 (core B) is a bipolar nebulosity which has a mass of 705 $M_\odot$ and dimensions of 3.3×1.5 pc^2. RNO9 is a nebulous, very red double star found to be associated with core C (mass 270 $M_\odot$ and size 1.7×1.3 pc^2). Kun, Wouterloot & Toth (2002) mapped L1340 in NH_3 and showed that core C is the densest with intense ammonia emission. The entire L1340 cloud hosts 22 IRAS point sources that are characterized as YSOs.

The optical CCD observations were made using Mosaic (8k×8k) on the 0.9 m telescope at Kitt Peak National Observatory covering approximately a 1^o field of view. Images were obtained in Hα, [S II], and Gunn z filters. NIR images in the K' filter were obtained with NICMOS-3 the 1.2 m telescope at Mt. Abu. We mapped the entire L1340 dark cloud optical wavelengths to look for HH objects and the three core regions were observed in the K' band.

We found from our observations that L1340 is an active star-forming cloud with three independent cores, showing various stages of low and intermediate mass star formation. Three HH flows (HH 487, 488, 489) are found in the southwestern part of the cloud (core A/RNO 7), which is currently forming low mass stars. HH 487 is a set of high excitation H-H bow shock features that likely originate from IRAS 02224+7227. HH 488 is a set of two flows that could be overlapping in the line of sight or physically associated with each other. It is ~3' in length and originates from sources that are yet to be detected. HH 489 is a flow of ~2' length originating from IRAS 02249+7230. We have shown for the first time that RNO 7 is a Herbig Be cluster of nearly 26 stars associated with core A (Fig 1(Right)). 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. 2002; Nandakumar, Anandarao & Yu 2002).

4. Massive and luminous YSO IRAS 05361+3539 and its environment

Massive YSOs are usually associated with ultracompact H II regions. They are mostly embedded deep inside clouds of gas and dust. It is possible to study the environment of these objects in the near-infrared using array detectors like NICMOS. Studies by Churchwell (1997) showed that massive YSOs display bipolar outflows like the low-mass YSOs, but the rate of mass outflow is larger in the former by orders of magnitude. Luminosities of massive YSOs are also higher. The total mass of the outflow is usually

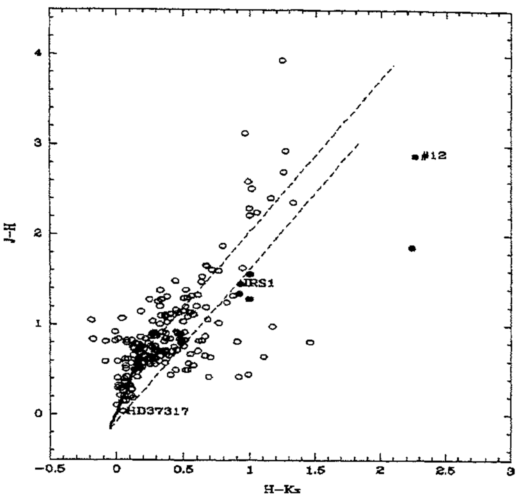

Figure 2. Color-Color diagram of the sources from the 2MASS data. The filled circles represent Class I type sources. The solid line represents unreddened main-sequence stars and the dashed lines are parallel to the reddening vector with magnitude of Av=30. Also shown are the positions of IRS1, Star # 12 (a possible FU Ori object)

larger than the central star. It is clear from earlier works (Churchwell 1997; Hunter et al 1997) that the impact of outflows from massive YSOs decides the fate of star-formation in the parent molecular cloud. We made a near-infrared study on the massive YSO IRAS 05361+3539 and tried to understand the star formation in the neighbourhood. For this purpose, we used the 2MASS data and new NIR observations from Mt. Abu. The source is situated at a kinematic distance of 1.8 kpc. The integrated far-infrared flux corresponds to a B2.5 central star(of mass $\sim$ 7 $M_{\odot}$). Shepherd & Churchwell (1996) found bipolar flows from the ^{12}CO velocity maps and estimated the outflow mass to be 32 $M_{\odot}$.

IRAS 05361+3539 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 v = 1-0 S(1)), 2.16 μm (Brγ),and 2.14 μm (continuum) on 25 February 2000. The J, H and K_s 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 the J-H *vs* H-K_s color-color diagram (Fig 2).

The parent molecular cloud is an active star forming region as evidenced from a number of PMS sources detected in our study: a total of 6 prospective Class I sources, including IRAS 05361+3539; and a number of faint Class II sources are detected in the region. One of the Class I sources (star 12 in Fig 2) detected close to IRS1 shows extreme reddening in the color-color plot. This YSO appears to be fainter by 1.1 magnitudes in both H and K' bands in the Mt. Abu images than in the 2MASS data. The time difference between the two observations was 23 months. Therefore, this YSO could be a variable protostar of the FU Orionis type. From the spectral energy distribution in the infrared region, we propose using a radiative model, 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).

Acknowledgements

It has been a pleasure working with my students Nanda and Abhijit without whose zeal and motivation this work would not have been possible. The work is supported by Department of Space, Government of India.

References

Anandarao, B.G, 1998, In Univ. Press, Hyderabad, Eds: P.C. Agarwal & P.R. Vishwanath, *High Energy Astronomy & Astrophysics*, page 287.

Andre, P. et al., 1990, *A & A*,**236**, 180.

Bence, S.J. et al., 1998, *MNRAS* **299** 965.

Burton, M.G., 1992 *Aust. J. Phys.***45**, 463.

Chakraborty, A., et al., 2000, *A & A*, **364**, 683.

Churchwell, E., 1997, *Ap.J.*, **479**, L59.

Hunter T.R. et al., 1997, *Ap. J*, **478**, 283.

Kun M. et al., 1994, *A & A*, **292**, 249.

Kun M., Wouterloot, J.G.A. and Toth, L.V., 2002, *A & A*, in press.

Lada C.J., In Kluwer, Dordrecht, Eds : C.J. Lada and N.D. Kylafis, *The Physics of Star Formation and Early Stellar Evolution*, page 329.

Nandakumar M.S., 1999, *Ph.D. Thesis, Gujarat Univ., Ahmedabad.*

Nandakumar M.S., Anandarao B.G., and Davis, C.J., 1999. *A & A.*, **344**, L9.

Nandakumar M.S., Anandarao, B.G., and Yu, K.C., 2002, *AJ*, May Issue.

Shepherd, D.S., and Churchwell, E., 1996, *ApJ*, **472**, 225.

Sternberg A. and Dalgarno, A., 1989, *ApJ*, **338**, 197.

Shull J.M. and Beckwith, S., 1982, *ARA & A*, **20**, 163.

Weintraub, D.A. et al., 1994, *ApJ*, **423**, 674.

Yonekura, Y. et al., 1997, *ApJ.*, **110**, 21.