Bulletin de la Société Royale des Sciences de Liège, Vol. 87, Actes de colloques, 2018, p. 257 - 261

A highly embedded protostar in SFO 18: IRAS 05417+0907

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Abstract: Bright-rimmed clouds, located at the periphery of relatively evolved HII regions, are considered to be the sites of star formation possibly triggered by the implosion caused due to the ionizing radiation from nearby massive stars. SFO 18 is one such region showing a bright-rim on the side facing the O-type star, λ Ori. A point source, IRAS 05417+0907, is detected towards the high density region of the cloud. A molecular outflow has been found to be associated with the source. The outflow is directed towards a Herbig-Haro object, HH 175. From the *Spitzer* and *WISE* observations, we show evidence of a physical connection between the molecular outflow, IRAS 05417+0907 and the HH object. The spectral energy distribution constructed using multi-wavelength data shows that the point source is most likely a highly embedded protostar.

1 Introduction

IRAS 05417+0907 (α_{2000} = 05h44m29.8s; δ_{2000} = +09d08m54s) is a luminous young stellar object (YSO) located in the tip part of a bright-rimmed cloud SFO 18, located at the edge of the large HII region, S264, excited by the massive O-type star λ Ori (Lada et al. 1981; Sugitani et al. 1991). It is embedded in dense gas and dust typical of a protostellar environment. A highly collimated outflow has been discovered in the H_2 line emission associated with the source. The size of the outflow is $\sim 7.14'$ or 0.83 pc, considering the distance of the cloud to be 400 pc (Murdin & Penston 1977). The emission lines of H_2 molecules may be due to the excitation of parental cloud material by the jet emission from this protostar.

Using the 13.7-m radio telescope at Taeduk Radio Astronomical Observatory (TRAO), we made mapping observations in the ^{12}CO (J = 1-0) line towards SFO 18. A 4×4 grid with 44" grid spacing was used in these observations. We conducted a multiwavelength study of IRAS 05417+0907, involving photometric data from the Two Micron All Sky Survey (2MASS), *Spitzer*, the Wide-field Infrared Survey Explorer (*WISE*), *Herschel*, and the Submillimetre Common-User Bolometer Ar-

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ray (SCUBA). We present preliminary results computed from the spectral energy distribution (SED) which reveals that the IRAS source is most likely in its early stage of evolution.

2 Observations and data reduction

2.1 TRAO Data

We carried out mapping observations of a region of $15' \times 30'$ around SFO 18 in ^{12}CO (J = 1-0) using the SEcond QUabbin Observatory Imaging Array (SEQUOIA) at TRAO which is a millimeter-wave radio observation facility with a single dish with a diameter of 13.7 m at the Korea Astronomy and Space Science Institute (KASI) in Daejeon, South Korea. The observed data is kept in the Continuum and Line Analysis Single-dish Software (CLASS) format. Data reduction was done by the CLASS software of the GILDAS package[1].

2.2 Archival Data

We acquired data from 2MASS, *WISE* and SCUBA using the VizieR tool[2].

We used archival data in the 3.6, 4.5, 5.8, and 8.0 μm wavebands taken with the Infrared Array Camera (IRAC; Fazio et al. 2004) of the space-based *Spitzer* telescope. This region was also observed with the Multiband Imaging Photometer for *Spitzer* (MIPS) at 24 μm. The basic calibrated data (BCD) were acquired from *Spitzer* Heritage Archive (SHA). Mosaicking in each wavelength was performed using the MOsaicker and Point source EXtractor (MOPEX) package provided by the *Spitzer* Science Centre (SSC) and photometry was done using APEX multiframe photometry, which is a part of MOPEX.

The HSA (*Herschel* Science Archive) User Interface (HUI) was used to acquire *Herschel* data for this source. The Photoconductor Array Camera and Spectrometer (PACS) observed it at 100 and 160 μm and the Spectral and Photometric Imaging Receiver (SPIRE) also detected it at 250, 350 and 500 μm. For the photometric analysis we used level 2 images of SPIRE and level 2.5 images of PACS which are processed images provided by the *Herschel* Science Archive (HSA) instead of raw level 0 images. Photometry was done using the task `annularSkyAperturePhotometry` in the Herschel Interactive Processing Environment (HIPE) software (14.1.0 version).

The TANSPEC (TIFR-ARIES Near Infrared Spectrometer), coupled with 3.6-m Devasthal Optical Telescope (DOT) is expected to reach a 5σ detection of 22.5 mag objects in the K band with a one hour exposure. IRAS 05417+0907 has a J band magnitude of $\sim$18.44 mag, which is an upper limit. So we expect to be able to achieve good photometric data of this source using TANSPEC with the 3.6-m DOT.

3 Results and discussions

3.1 The Source Driving The Outflow

We identify the source detected in the *Spitzer* data as a Class 0/I protostar, deeply embedded in the tip part of the cloud SFO 18, driving the outflow. The IRAC ([5.8-8.0], [3.6-4.5]) color-color diagram can be used to roughly determine different evolutionary stages of identified YSOs. Fig. 1 shows the IRAC colors of the sources, located within a field of 8.8’$\times$8.8’ around the protostar. The red dashed

[1] `http://www.iram.fr/IRAMFR/GILDAS`
[2] `http://vizier.u-strasbg.fr/`

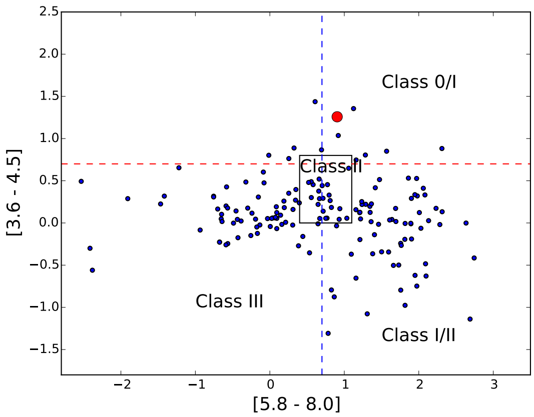

Figure 1: The color-color diagram of IRAS 05417+0907 using the *Spitzer* 3.6, 4.5, 5.8 and 8.0 μm wavebands. IRAS 05417+0907 is indicated by a red dot.

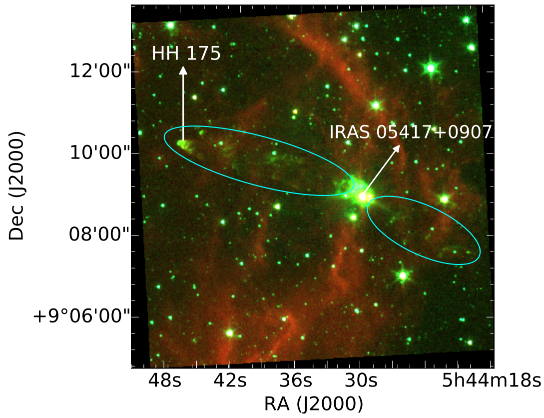

Figure 2: A color-composite image of IRAS 05417+0907 associated with the outflow. The image is produced from *Spitzer*-IRAC data adopting blue, green and red for the 3.6, 4.5 and 8.0 μm images, respectively.

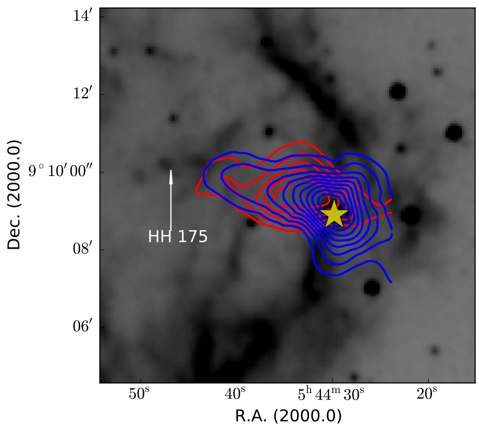

Figure 3: Contour map of ^{12}CO (J=1-0) line wing integrated intensity in IRAS 05417+0907 overplotted on the WISE 12 μm 0.5°×0.5° image. The redshifted and blueshifted lobes are indicated by red and blue lines, respectively. Blueshifted contours are from 1.2-10.2 Kkms^{-1} in steps of 1 Kkms^{-1} and redshifted contours range from 1.7-6.6 Kkms^{-1} in steps of 1 Kkms^{-1}. The yellow star marks the IRAS source.

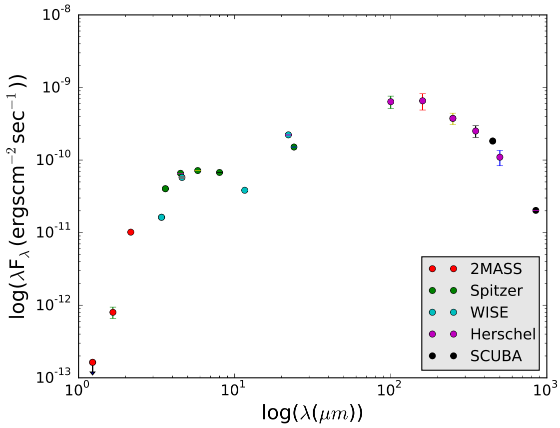

Figure 4: The SED of IRAS 05417+0907 constructed using 2MASS, *Spitzer*, *WISE*, *Herschel* and SCUBA photometric data. 2MASS J band magnitude gives an upper limit, so its corresponding flux is marked as a downward arrow.

Table 1: Outflow Parameters for the blueshifted (top line) and redshifted (bottom line) lobe associated with IRAS 05417+0907. For each lobe we give the size, the mass M, the momentum P, the energy E, the radial velocity V, the age t, the force F, the mechanical luminosity L_{mech} and the mass loss rate M_{loss}.

Lobe	size (pc)	M ($M_\odot$)	P ($M_\odot$kms^{-1})	E (erg)	V (kms^{-1})	t (Myr)	F ($M_\odot$kms^{-1}yr^{-1})	L_{mech} ($L_\odot$)	M_{loss} ($M_\odot$yr^{-1})
Blue	0.5	0.2	0.7	0.2	3.3	0.15	0.5×10^{-6}	0.1×10^{-2}	1.3×10^{-7}
Red	0.8	0.5	2.0	0.9	4.1	0.19	1.1×10^{-6}	0.4×10^{-2}	2.6×10^{-7}

horizontal line represents the boundary between Class I/II and Class III (below) and Class 0/I objects (above). The blue dashed vertical line differentiates more evolved Class III sources from younger Class 0/I and Class I/II sources. The rectangle distinguishes the Class II sources from other YSOs (see Megeath et al. 2004). The location of IRAS 05417+0907, indicated by a red dot, suggests that it is a highly embedded protostar.

3.2 The Outflow

The *Spitzer* 4.5 μm image reveals a spectacular outflow oriented in northeast-southwest direction associated with IRAS 05417+0907 which can be seen in the color-composite image using *Spitzer* 3.6 (blue), 4.5 (green) and 8.0 (red) μm images (Fig. 2). The northeastern part of the outflow ends with a Herbig-Haro object HH 175. The southwestern part is not as much prominent as the other one which may be due to the absence of cloud material in this direction.

The outflow parameters associated with the infrared source have been calculated using ^{12}CO (J=1-0) data. With line center radial velocity at V_{LSR} of 11.8 kms^{-1}, the line wings are integrated from 6-10.5 kms^{-1} (blue wing) and from 13.5-18 kms^{-1} (red wing). Contours of line wing emission (redshifted and blueshifted) have been shown in Fig. 3.

From Table 1, we can see the that the outflow has a significantly lower mass M and mass loss rate M_{loss} than those of massive YSOs (Wu et al. 1996). Moreover, low mass sources make up 90% of outflows associated with HH objects (Wu et al. 2004) which is the case for IRAS 05417+0907. So, we can consider it to be a young low mass star.

3.3 The Spectral Energy Distribution:

The 2MASS 1.23-2.16 μm, *Spitzer* 3.6-8.0 and 24 μm, *WISE* 3.4-22.1 μm, *Herschel* PACS 100 and 160 μm and SPIRE 250, 350 and 500 μm, and SCUBA 450 and 850 μm data were used to develop the SED of the IRAS source shown in Fig. 4. The bolometric temperature (T_{bol}) is calculated following the method written in Myers & Ladd (1993). The bolometric luminosity (L_{bol}) is calculated by integrating over the full SED, and multiplying the result with $4\pi D^2$, where the D is the distance of the protostar (400 pc). The submillimeter luminosity (L_{submm}) is calculated by integrating over the SED for $\lambda \geq$ 350 μm.

4 Conclusions

1. IRAS 05417+0907 is a luminous YSO which is forming through accretion of the circumstellar disk in the parental cloud SFO 18. A highly collimated outflow has been discovered associated with this protostar in *Spitzer* 4.5 μm. The northeastern part of this outflow ends with a Herbig-Haro object HH 175. The southwestern part of the outflow is not as much visible as the northeastern part. The excitation of H_2 molecules by the jet might be less efficient here due to the absence of the cloud material.
2. The SED constructed from multi-wavelength data shows that IRAS 05417+0907 is probably a highly embedded YSO, which is also supported by its location in *Spitzer* color-color diagram (red dot in Fig. 1).
3. From the SED we estimated that L_{bol} = 11.7$L_{\odot}$, L_{bol}/ L_{submm} = 16.8, and T_{bol} = 64.2 K. Chen et al. (1995) grouped all YSOs with $T_{bol} <$ 70K as Class 0 protostars. According to Andre et al. (1993), YSOs with L_{bol} / $L_{submm} <$ 200 are Class 0 protostars. So, the *Spitzer* color-color diagram and physical parameters mentioned above indicate that IRAS 05417+0907 is most likely in its early stage of evolution.

Acknowledgements

This work made use of 2MASS, *WISE* and SCUBA data downloaded from SIMBAD database operated by CDS, Strasbourg, France. This is also based on archival data of *Spitzer* Space Telescope, operated by the Jet Propulsion Laboratory, California Institute of Technology. The *Herschel* data were obtained from *Herschel* Science Archive (HSA). ^{12}CO (J = 1-0) molecular line data were acquired using TRAO at KASI, Daejeon, South Korea.

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