Geometrical and kinematical structures abound class 0 objects

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Abstract

Class 0 objects are regard as the youngest protostars on their evolutional phases. They are so deeply embedded in molecular gas and dust that they have been believed to be invisible in optical and near-IR. Recent deep near-IR observations (particularly by the *Spitzer Space Telescope*) have revealed that they are, in fact, detectable in near-IR as scatted light emerging from their envelope cavities. mm and submm observations show that they are actively driving molecular outflows, and besides, they have infalling material implied by asymmetric double-peaked profiles of optically thick lines. In spite of their thick envelopes, near-IR detection is a common feature for the nearby class 0 objects probably due to widely open outflow cavities.

Introduction

The youngest protostar, called class 0 object, is characterized by its cold bolometric temperature derived from the broadband spectral energy distribution (SED). Because it is on the main accretion phase and embedded in thick gas and dust envelope, far-IR and submm emissions dominate the SED, and thus, cold gray-body spectra is obtained. One of the conceptual definition of the class 0 object is that the central object mass is less than the envelope mass, which yields bolometric temperature, T_{bol} < 70 K. It has a central object in the hydrostatic equilibrium which is the heating source and driving molecular outflow. It is observed as a (sub)mm point source with energetic infalling and outflowing gas motion.

A prototype class 0 object, Lupus 3 MMS

The prototype class 0 object, Lupus 3 MMS, was found as a result of a series of radio survey. Based on the $C^{18}O$ core surveys by the NANTEN radio telescope, (Hara et al. 1999), the Lupus 3 cloud were surveyed for denser and more compact cores and embedded young protostars in $H^{13}CO^+$ (J=1–0) and 1.2 mm continuum by the SEST 15m telescope at La Silla. These resulted in finding 3 dense cores and an embedded protostellar point source. From the broadband SED analysis of the photometric data obtained by SEST, ESO/NTT, *Spitzer Space Telescope* (*SST*), and *IRAS*, this mm source turned out to be a cold and faint class 0 object with T_{bol} = 39.5 K and L_{bol} = 0.16 $L_{\odot}$ (Tachihara et al. 2007).

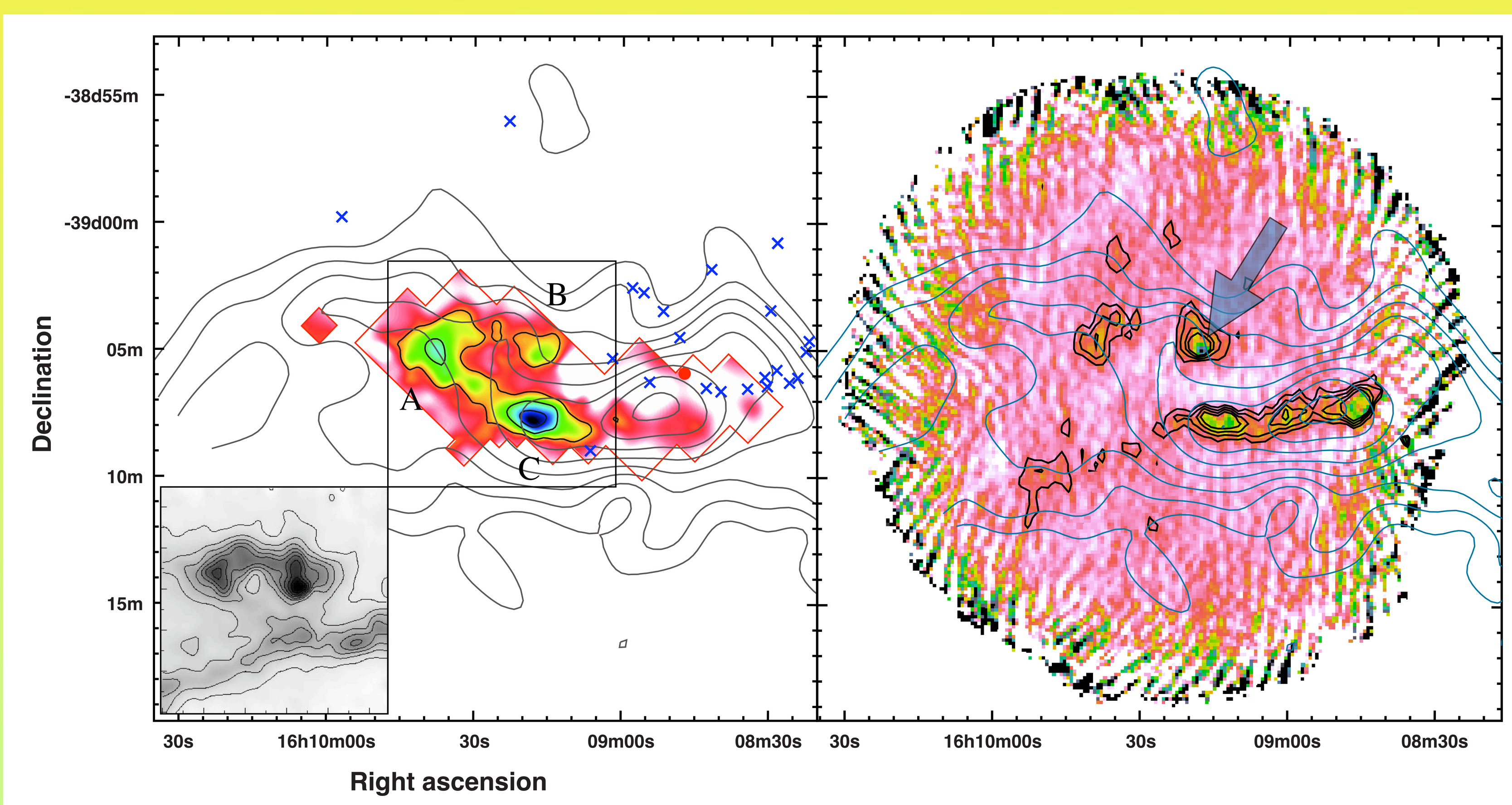

Fig. 1: Results of the SEST observations in the Lupus 3 cloud. Left: $H^{13}CO^+$ integrated intensity map is shown as pseudo color image and contours (0.2 K km s^{-1} each) overlaid on the $C^{18}O$ contours (integrated intensity of 0.3 K km s^{-1} each) taken with the NANTEN telescope (Hara et al. 1999). The border of the surveyed area is illustrated by the red lines. The blue crosses and red circle are T Tauri stars (Hughes et al. 1994) and the IRAS point source 16054–3857. The central box denotes the area covered by the A_V map of Nakajima et al. (2003), shown inset. Right: 1.2 mm continuum SIMBA map is shown as pseudo color image. Contours are from 0.035 mJy beam^{-1} to 0.14 mJy beam^{-1} with 0.035 mJy beam^{-1} steps excluding the border of the field of view. Overlaid are the the $C^{18}O$ contours same as the left. The MMS is indicated by the arrow.

Class 0 objects are visible in near- and mid-IR

In the conventional idea, class 0 objects were regarded as being embedded too deeply to be detected in wavelengths shortward of near-IR. The model was, however, constructed based on simple assumption with spherically symmetric envelope, regardless of disks, outflows, and their cavities. Many author have suggested that their SED are subject to change depending on their geometrical structures and the viewing angles (Masunaga & Inutsuka 2000; Nakazato et al. 2003; Whitney et al. 2003). In particular, near-IR scatted light is obviously detectable if outflow cavities are large enough. The Lupus 3 MMS is detected in all bands of λ > 2 μm.

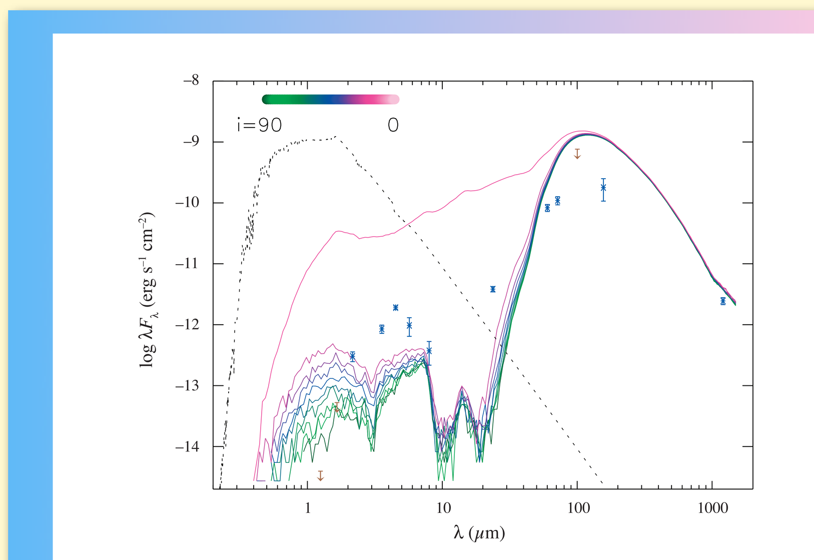

Fig. 2: The SED of the Lupus 3 MMS. The photometric data are plotted on the calculated class 0 SED with different viewing angles shown by different colors (Whitney et al. 2003).

Geometrical and kinematical structures of the Lupus 3 MMS

Fig. 3 left shows 3 color image (*K*-band, 3.6, and 4.5 μm) of the Lupus 3 MMS. The class 0 object is clearly seen in the near-IR as a nebulosity of scatted light emerging through the outflow cavities. The *K*-band nebula corresponds to the blue-shifted outflow wing, implying that the light only from the near-side cavity is visible through less extinction, while the 4.5 μm fan-shaped nebula has a bipolar structure. The cavities have a projected opening angle of ~ 45 deg. The blue- and red-shifted outflow lobes are well separated centered at the position of 1.2 mm, near-IR, and HCO^+ peaks. The elliptical 8 μm shadow implies that it has flattened circumstellar envelope perpendicular to the outflow direction. These geometrical and kinematical structures suggest that Lupus 3 MMS has relatively large inclination angle close to edge-on. The scattered light in near-IR is, however, much brighter than the model calculation with large inclination (Fig. 2). This is probably due to the wider opening angle of the outflow cavity than that in the model.

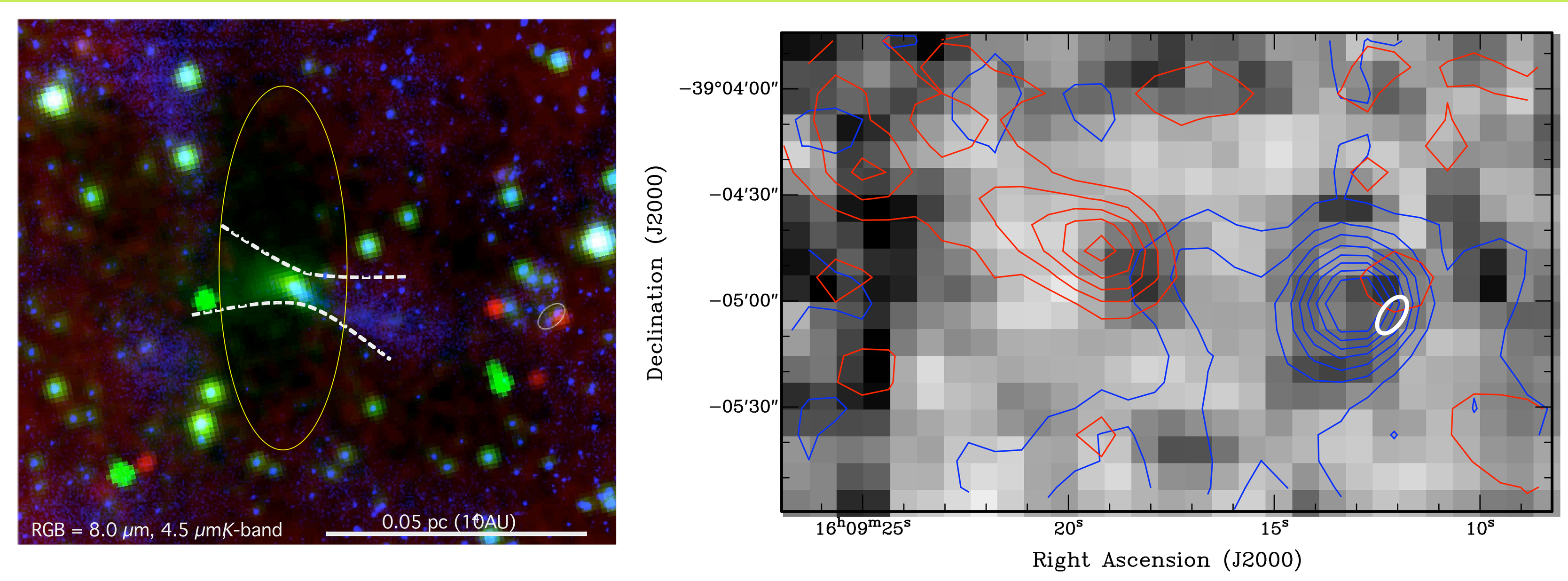

Fig. 3 (left): Composite 3 color image (*SST* 8.0 μm in red, 4.5 μm in green and NTT K_s band in blue) around the MMS. The white-dashed parabolic lines denote the outlines of the fan-shaped nebulosities, whose opening angle is ~ 45°. The yellow ellipse illustrate the dark shadow visible in 8 micron. The white small ellipse shows the position of HH 78. (right): Results of submm observations of Lupus 3 MMS by ASTE. HCO^+ (J=4–3) integrated intensity is shown in gray background overlaid with CO (3–2) blue- and red-shifted outflow lobes. The white ellipse shows the position of HH 78.

Discussion

How common are the class 0 objects visible in near-IR? Almost all nearby class 0 objects are detected in 3.6 and 4.5 μm (some are also in *H* and *K* bands) even if they have nearly edge-on configurations such as VLT 1623 as indicated by the well-collimated and separated outflow lobes (Fig. 4). In many cases, nebulae of short-wavelength scattered light are visible in directions of blue-shifted (thus near-side) outflow lobes. The nebulae have fan-shaped structures with relatively wide (~ 90°) opening angles. L1521F exhibits asymmetric double peaked profiles of HCO^+, which is a signature of the infalling material as expected from being on the main accretion phase for class 0 objects.

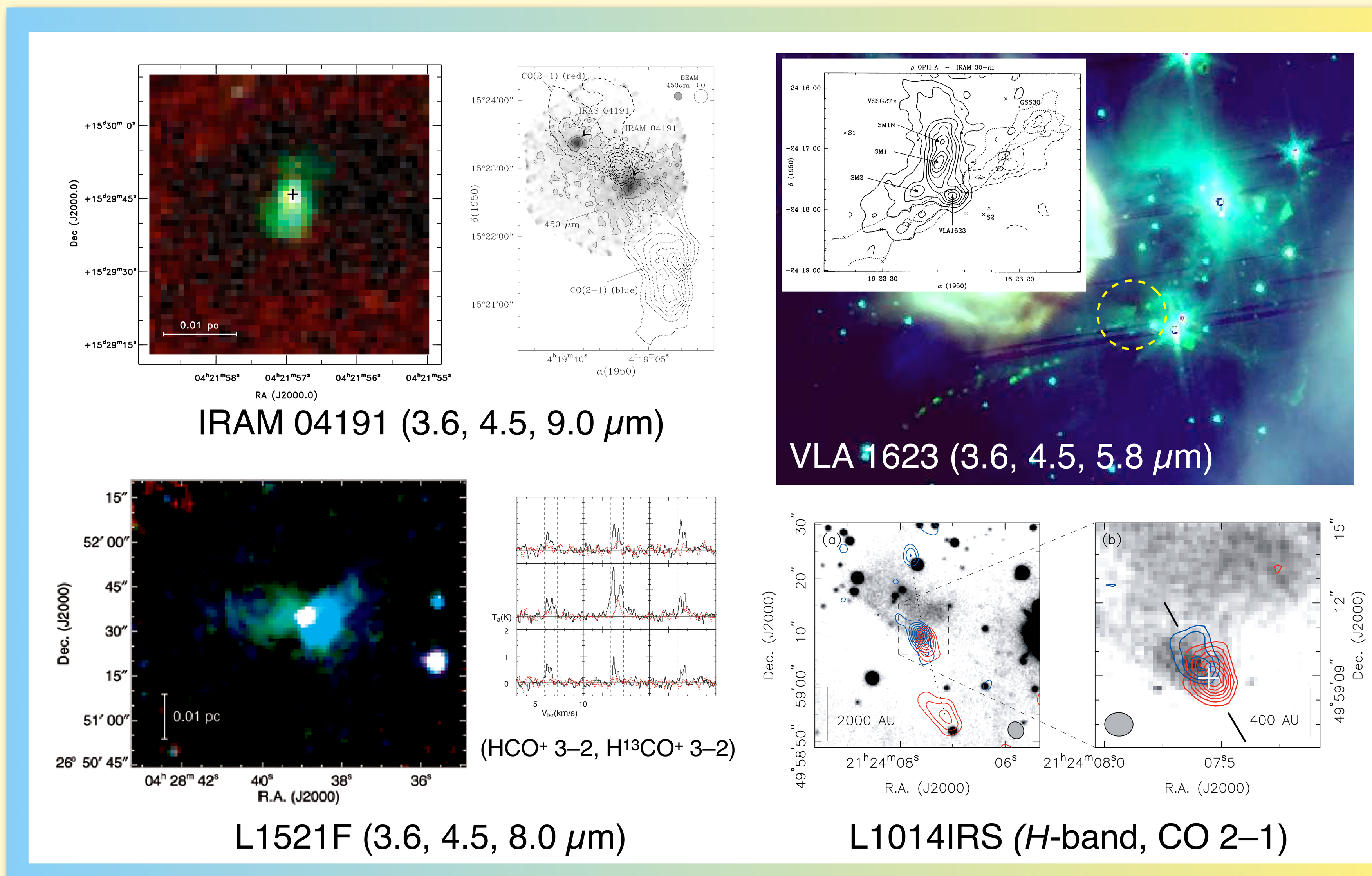

Fig. 4: Gallery of the representative nearby class 0 objects observed in near-IR (Dunham et al. 2006; Bourke et al. 2005, 2006). Maps of molecular outflows are also shown for IRAM 04191 (André et al. 1999), VLA 1623 (André et al. 1993), and L1014-IRS, while L1521F is demonstrated with the HCO^+ double-peaked spectra (Onishi et al. 1999).

Conclusion

On the contrary to the previous consensus, many class 0 objects are, in fact, detected in near-IR bands especially by *SST*. It is probably due to wide opening angle of the outflow cavities that enable the scattered light from the central object to emerge out of the thick envelopes. This is contradictory to the conventional model of jet and outflow, and the definition of class 0 object should be reconsidered. The model SED should also be revised with the help of observational data. High resolution observations by ALMA will bring us knowledge of detailed 3-dimensional geometrical and kinematical structures of class 0 objects, which will lead us understand physical properties of very young protostars.