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H_2 and methanol masers - outflow from the earliest stages of high-mass star formation?

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Abstract. We report the discovery of shocked H_2 emission at 2.12 μm associated with methanol masers, and discuss its implication for massive star formation.

1. Introduction

The relationship of two signposts of high-mass star formation, ultracompact (UC) H II regions and 6.7 GHz methanol maser emission, were investigated by Walsh et al. (1997, 1998) through low and high spatial resolution radio surveys. They showed that methanol maser emission does occur in massive star forming regions but *away* from UC HII regions. A hypothesis has emerged that methanol maser emission is the first prominent signature of massive star formation, being quickly destroyed as the UC HII region evolves. To test this hypothesis we looked for other indicators of star formation, such as embedded IR sources and outflows. We report the discovery of H_2 emission associated with methanol masers, a tracer of outflow activity.

2. Observations

The four IRAS sources from radio surveys of Walsh et al. (1997, 1998) were observed in H_2 1–0 S(1) 2.12μm line emission using a NIR narrow-band tunable filter UNSWIRF[2] on the Anglo-Australian Telescope. Used at f/36, the UNSWIRF produced a circular image of 100″ diameter at 0.8″ pixelscale. One off-line setting (for continuum subtraction) and several on-line Fabry-Parot (FP)

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[2] The University of New South Wales Infrared Fabry-Parot (Ryder et al. 1998)

spacings, were taken for a few minutes first on a source and then on a sky position (for sky subtraction). A standard star was imaged at each of the FP settings for flux calibration, as was a diffuse dome lamp to obtain a flat field. The sky-subtracted and flat-fielded object frames were registered using field stars in the continuum frame. The continuum frame is scaled and subtracted from all other on-line frames to form a cube in increasing etalon spacing, from which the line flux and central velocities of the H_2 emission were determined through Lorentzian fitting.

3. Results

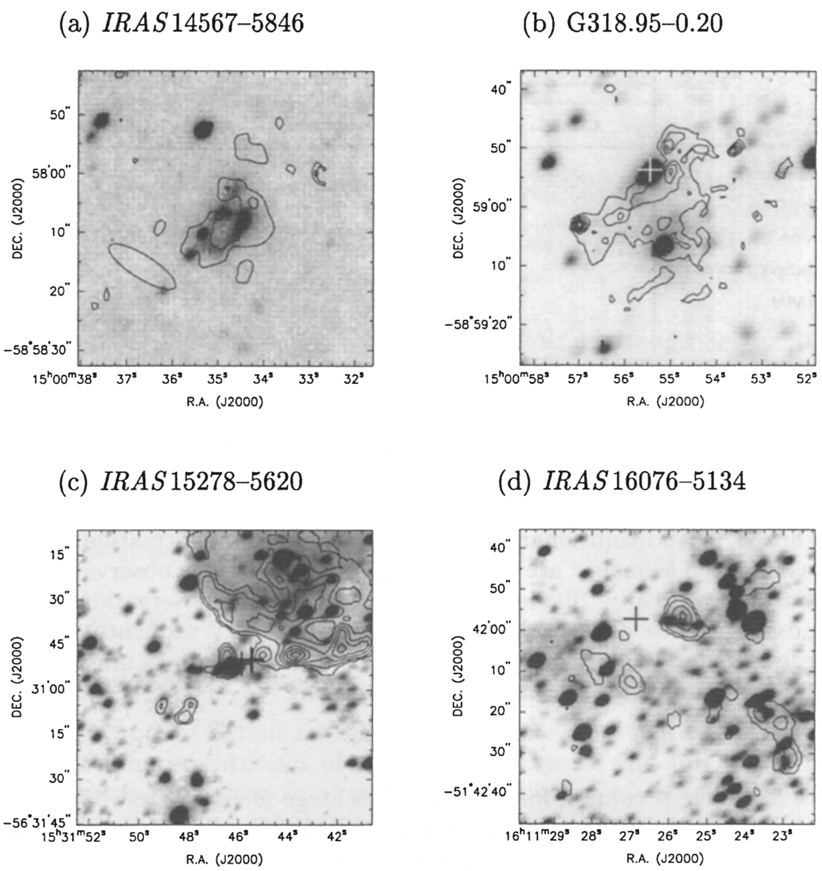
All the sources observed with the UNSWIRF show H_2 line emission associated with them (intensity maps in Fig. 1; Refer to Lee al al. (2001) for velocity maps). *IRAS* **14567–5846** is associated with a large bright cometary UC HII region, but not with methanol maser emission. Fig. 1(a) shows weak H_2 emission appears to surround the UC HII region (in 2.2μm K-band continuum emission) in a shell. No significant velocity structure was seen in this source. A maser site **G318.95–0.20**, 2.5′ SE of *IRAS* 14567, is coincident with strong H_2 emission extending over 30″ (Fig. 1(b)). No radio continuum emission is found at this site (Ellingsen et al. 1996). Due to insufficient FP coverage, we only note that the velocity of the H_2 emission extends over at least 50 km s^{-1}.

Two methanol maser sites separated by 5″, found in *IRAS* **15278–5620** are associated with two embedded NIR sources (Fig. 1(c)). The UNSWIRF observation reveals fan-shaped H_2 emission NW of the maser sites, associated with K-band continuum nebulosity, and weak emission to the SE. The velocity maps (not shown here) show three components with the line centre velocities smoothly changing over about a 70 km s^{-1} range: Two red-shifted components to the SE and ~ 30″ N, and one blue-shifted to the NW of the maser sites. In *IRAS* **16076–5134**, a slightly elongated blob 10″ to the west of the maser site emits in H_2 line and K-band continuum emission (Fig. 1(d)). The H_2 line centre velocities range over 13 km s^{-1}, red-shifted relative to the maser emission velocity. Weaker H_2 emission is also detected to the SW of the maser site.

4. Discussion

In this section we briefly discuss the excitation mechanism of the H_2, and its role in the sequence of events that produces massive stars. For more detailed discussion, refer to Lee at al. (2001). The 1–0 S(1) to 2–1 S(1) line ratio of H_2 is often used to distinguish between the two excitation mechanisms, namely UV fluorescence and collision in shocks. With no 2–1 S(1) line intensity available, we rely on morphology and line velocities to infer the origin of the H_2 emission. UV fluorescence seems likely for *IRAS* 14567, where the H_2 emission appears to surround the UC HII region forming a photo-dissociation region (PDR). In all other cases, non-detection of radio continuum emission i.e. the absence of UV photons, is suggestive of shock excitation of H_2 the most likely mechanism. In addition, the broad line width of H_2 line emission also favours shock-excitation.

For the origin of methanol maser emission, Walsh et al. (1997, 1998) proposed a pre-UC HII region hypothesis where the maser emission turns on during


(a) *IRAS* 14567–5846

(b) G318.95–0.20

(c) *IRAS* 15278–5620

(d) *IRAS* 16076–5134

Figure 1. Four sources observed in H_2 1-0 S(1) line emission with the UNSWIRF are presented in contours. The underlying greyscale maps show 2.2μm K-band continuum emission. The ellipse in (a) indicates the *IRAS* error ellipse, and the plus signs mark the position of methanol maser sites.

the protostellar phase before an UC HII region does. Our UNSWIRF observations show that all the the methanol maser emission is associated with (presumably shocked) H_2 emission that seems associated with the powering sources of outflows. Outflows occur only during an early stage of star formation, thus our results support the pre-UC HII origin of the methanol maser emission.

Compact and dense hot molecular cores (HMCs) are suggested not only to be sites of massive star formation, but may also represent an earlier stage in the star formation process than UC HII regions. If both HMCs and methanol maser emission were early signatures of high-mass star formation, how are they related? We propose that the formation of high-mass stars begins in HMCs where 1) heat from contraction releases methanol from grain surfaces into the gas phase, 2) the gas is compressed, by outflows and/or in circumstellar disks,

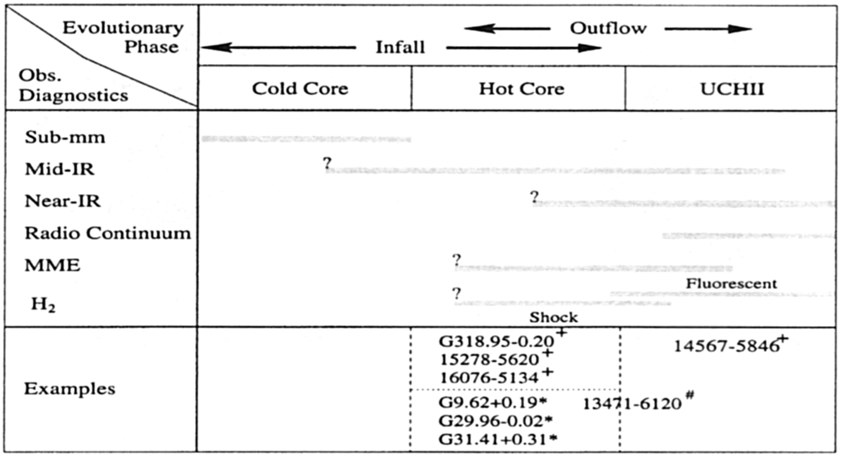


Figure 2. An evolutionary sequence to massive star formation. The phases in the sequence are listed horizontally and their observational signatures vertically. Shaded areas indicate when an observational diagnostic may be observable during the evolutionary sequence. The question mark is used when the beginning of the phase is uncertain, and MME stands for methanol maser emission.

to create a sufficient column for masing. This stage is signposted by methanol maser emission and shocked H_2 line emission. 3) As the UC HII region develops and expands, it turns off methanol maser emission and forms a PDR envelope where H_2 is excited by UV fluorescence (summarised in Figure 2). A test for such a scenario is to look for cold molecular cores (earlier phase than HMCs in star formation sequence) associated with methanol maser emission. In addition, spectral energy distributions, thus spectral types, of the powering sources would enable us to discern between the pre-UC HII origin and non-ionizing star origin for methanol maser emission.

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