Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **435,** 524–530 (2013)
Advance Access publication 2013 August 13

doi:10.1093/mnras/stt1315

Confirmation of the exclusive association between 6.7-GHz methanol masers and high-mass star formation regions

S. L. Breen,[1]★ S. P. Ellingsen,[2] Y. Contreras,[1] J. A. Green,[1] J. L. Caswell,[1]
J. B. Stevens,[3] J. R. Dawson[2] and M. A. Voronkov[1]

[1] *CSIRO Astronomy and Space Science, Australia Telescope National Facility, PO Box 76, Epping, NSW 1710, Australia*
[2] *School of Mathematics and Physics, University of Tasmania, Private Bag 37, Hobart, Tasmania 7001, Australia*
[3] *CSIRO Astronomy and Space Science, Australia Telescope National Facility, Locked Bag 194, Narrabri, NSW 2390, Australia*

Accepted 2013 July 16. Received 2013 July 16; in original form 2013 May 25

ABSTRACT

Recently, a comparison between the locations of 6.7-GHz methanol masers and dust continuum emission has renewed speculation that these masers can be associated with evolved stars. The implication of such a scenario would be profound, especially for the interpretation of large surveys for 6.7-GHz masers, individual studies where high-mass star formation has been inferred from the presence of 6.7-GHz methanol masers and for the pumping mechanisms of these masers. We have investigated the two instances where 6.7-GHz methanol masers have been explicitly suggested to be associated with evolved stars, and we find the first to be associated with a standard high-mass star formation region, and the second to be a spurious detection. We also find no evidence to suggest that the methanol maser action can be supported in the environments of evolved stars. We thereby confirm their exclusive association with high-mass star formation regions.

Key words: masers – stars: formation – ISM: molecules.

1 INTRODUCTION

Since their initial discovery, methanol masers in the 6.7-GHz (5_1–6_0 A$^+$) transition (Menten 1991b) have been considered one of the best tracers of star formation. Methanol masers are divided into two classes, originally reflecting their different locations with respect to the associated young stellar object (YSO; Menten 1991a), but which are now understood to reflect their differing pumping mechanisms. The 6.7-GHz transition is the strongest and most widespread of all the class II (radiatively pumped) methanol masers and are considered to be exclusively associated with high-mass star formation regions (e.g. Minier et al. 2003; Xu et al. 2008; Gallaway et al. 2013). Although a number of observations have targeted low-mass star formation regions (e.g. Minier et al. 2003; Bourke, Hyland & Robinson 2005; Green et al. 2012a) no sources of 6.7-GHz methanol maser emission have been detected to date, nor are they expected given the temperatures and methanol column densities required to produce class II methanol maser emission (e.g. Cragg, Sobolev & Godfrey 2005).

While it is widely accepted that low-mass YSOs are unable to produce class II methanol masers, the lower mass limit on the stars that can produce them is not well constrained. Minier et al. (2003) detected a low-luminosity 6.7-GHz methanol maser towards the Orion B region (NGC 2024:FIR 4). This is thought to be an intermediate-mass protostar, although its true nature remains enigmatic (see discussion in Minier et al.). High-resolution images of some 6.7-GHz methanol masers show simple velocity gradients which have been interpreted as being due to the molecular gas lying within a rotating disc (e.g. Minier, Booth & Conway 1998). The mass inferred when the linear extent and velocity gradient of the 6.7-GHz methanol masers are fitted by Keplerian rotation is typically less than 8 $M_\odot$ (e.g. Minier, Booth & Conway 2000; Goddi, Moscadelli & Sanna 2011), the lower limit of what is generally considered a high-mass star. However, this is likely the result of one or more of the many assumptions made in the fitting process (particularly that the masers trace the full extent of the disc), as the bolometric luminosity of the associated protostars and/or associated molecular outflows generally suggest the presence of a high-mass protostar at the location of the 6.7-GHz methanol masers. In contrast to the class II transitions, class I methanol masers have been detected towards low-mass star formation regions (Kalenskii et al. 2010), although they have much lower luminosities than those associated with high-mass star formation regions. Widespread class I maser emission from the 36 GHz transition has also recently been detected towards the Galactic Centre region (Yusef-Zadeh et al. 2013).

From the observations outlined above we can clearly infer that class I methanol maser transitions can be inverted in a variety of astrophysical environments, and are not exclusively associated with high-mass star formation. Class II methanol masers are radiatively pumped and generally have a much more restricted distribution

---

★ E-mail: Shari.Breen@csiro.au

Published by Oxford University Press on behalf of the Royal Astronomical Society

within high-mass star formation regions than the class I transitions (e.g. Cyganowski et al. 2009). Recently the exclusivity of the association of class II methanol masers with high-mass YSOs has been questioned by the suggestion that these masers could also be associated with evolved stars (Walsh et al. 2003; Urquhart et al. 2013). In both cases, the absence of any detectable dust continuum emission is integral to the questions raised about the nature of the sources.

Urquhart et al. (2013) compared complete samples of methanol masers (Caswell et al. 2010, 2011; Green et al. 2010) and 870-µm continuum emission (ATLASGAL; Schuller et al. 2009; Contreras et al. 2013). They found 577 methanol masers had accompanying dust continuum emission and identified 43 methanol masers devoid of dust continuum emission. In the majority of cases Urquhart et al. (2013) were able to identify diffuse, or weak compact emission at the location of the 43 methanol masers and concluded that the lack of an associated 870-µm point source (Contreras et al. 2013) was mostly due to these sources being located at much larger distances. Urquhart et al. (2013) find that this explanation is unsatisfactory for a small number of sources, and remark that another possibility is that these masers arise in the circumstellar shells associated with evolved stars.

Of the 43 methanol maser sources that Urquhart et al. (2013) find to have no accompanying dust continuum emission (Contreras et al. 2013), 10 had been reported previously at other wavelengths. One of these shows *IRAS* emission; two sources were detected in the Bolocam Galactic Plane Survey (detected due to its sensitivity to low surface brightness objects being superior to ATLASGAL; Aguirre et al. 2011) and seven are listed in the intrinsically red source compilation of Robitaille et al. (2008). Of the seven sources in Robitaille et al. (2008), six are identified as YSOs and a further source is listed as a possible asymptotic giant branch (AGB) star (G 328.385+0.131). Urquhart et al. (2013) use the point-like nature of the GLIMPSE 8.0-µm emission coincident with this source to assert that this object is indeed an evolved star, since they expect 8.0-µm emission associated with high-mass star formation regions to be extended.

Previously, Walsh et al. (2003) conducted 450-µm and 850-µm dust continuum observations with Submillimetre Common-User Bolometer Array on the James Clerk Maxwell Telescope towards 71 methanol masers, identifying one 6.7-GHz methanol maser site that was not associated with any sub-mm continuum emission. The methanol maser, G 10.10+0.73, was discovered in Parkes observations towards IRAS 18021−1950 (Walsh et al. 1997) and later followed up with the Australia Telescope Compact Array (ATCA) to determine a precise position (Walsh et al. 1998). While Walsh et al. (2003) failed to detect any sub-mm continuum emission associated with the methanol maser, they did detect a compact source within the target field (offset 90 arcsec from the methanol maser), associated with the bipolar planetary nebula NGC 6537. The authors question whether there is an association between the methanol maser and the planetary nebula, suggesting that the kinematics are well matched but maintaining that a chance alignment is a possibility. Urquhart et al. (2013) claim that this source supports their inference that methanol masers may be associated with evolved stars.

Here we present some general arguments as to why evolved stars are unlikely to harbour 6.7-GHz methanol masers (Section 2), briefly discuss the dust properties in star formation regions (Section 4.1.3) and then focus our investigation on the two 6.7-GHz methanol masers, G 328.385+0.131 (Section 4.1) and G 10.10+0.73 (Section 4.2), where an association with evolved stars has been explicitly suggested (Walsh et al. 2003; Urquhart et al. 2013).

2 METHANOL AND LATE-TYPE STARS

OH and water masers are observed in a wide range of astrophysical environments – from star-forming regions (both low and high mass in the case of water masers), evolved stars, supernovae remnants (1720-MHz OH) and the central regions of active galaxies. The 6.7-GHz methanol transition has been shown to be strongly inverted over a broad range of physical conditions (e.g. Cragg, Sobolev & Godfrey 2002), similar to the ground-state OH and 22-GHz water transitions. Therefore, it is natural to ask the question: are there astrophysical environments, other than those associated with high-mass star formation regions, which can support 6.7-GHz methanol masers?

There are nearly 1000 known 6.7-GHz methanol maser sources (Caswell et al. 2010, 2011; Green et al. 2010, 2012a) and in excess of 2000 late-type stars known to exhibit maser emission – primarily found from searches for 1612-MHz OH (Sevenster et al. 1997a,b, 2001) or SiO (e.g. Deguchi 2007) maser transitions. To date, no overlap between the 6.7-GHz methanol masers and evolved stars showing either 1612-MHz OH or SiO maser emission has been identified. Given the large size of both maser samples, and their typical positional accuracies of ∼1 arcsec, we can conclude that evolved stars showing 1612-MHz OH or 43-GHz SiO masers do not have conditions which are suitable for 6.7-GHz methanol masers.

For a molecular transition to exhibit maser emission requires both suitable physical conditions (temperature, density, etc.), and also a sufficient abundance of the relevant molecule. As evolved stars host maser emission in a range of ground-state OH transitions, as well as water and SiO, it would seem likely that some regions within that environment will have the temperatures and densities within the broad range necessary to support 6.7-GHz methanol masers. The critical difference between methanol and either OH or water seems to be that methanol is less readily produced in high abundance than either OH or water.

Garrod et al. (2006) summarize the evidence as to why methanol is thought not to be produced in gas phase reactions in the interstellar environment. The favoured mechanism for the formation of methanol is through hydrogenation of CO when it freezes out on dust grains (e.g. Tielens & Whittet 1997). Low grain temperatures favour the formation of formaldehyde and methanol rather than CO_2 (Hudson & Moore 1999; Taquet et al. 2013), and in some very young star formation regions infrared spectroscopy has found methanol ice to be the second most abundant ice on dust grains, after water (Dartois et al. 1999). Methanol ice has been observed towards both low- and high-mass star formation regions (e.g. Gibb et al. 2004; Pontoppidan, Dishoeck & Dartois 2004). As the forming stars heat the surrounding medium the methanol desorbs from the dust grains and is released into the gas phase. Mechanical desorption of the dust grains by outflows is also possible (e.g. Gibb & Davis 1998) and can play an important role in increasing the methanol abundance in the gas phase in some sources.

Similar to star formation regions, the environment near evolved low-mass stars contains large amounts of dust; however, it is not expected to be at temperatures of around 10 K, which favour the formation of methanol on the grain mantles (e.g. Taquet et al. 2013). Amongst evolved star maser sources, a small number show emission in atypical maser transitions, for example the proto-planetary nebulae K 3-35 possesses 1720 MHz and 6 GHz excited OH masers (Desmurs et al. 2010). Some very young planetary nebulae and proto-planetary nebulae also have associated cold dust (Sahai & Nyman 1997); however, the dust masses are very much less than 1 $M_\odot$ and are unlikely to facilitate the formation of large amounts of methanol ice. To date, there have been no detections of methanol towards any evolved stars, despite sensitive measurements towards a number of nearby sources (e.g. Ford et al. 2004; He et al. 2008). In particular, observations towards the extreme carbon star IRC+10216 (towards which more than 50 molecular species have been observed) failed to detected any methanol with a 3σ abundance upper limit of 8.5×10^{-10} (although the same observations detected formaldehyde with more than an order of magnitude greater abundance).

In summary, current understanding of the formation process for methanol in astrophysical environments suggests that it is unlikely to be present in the vicinity of evolved stars and this is supported by existing observational studies.

3 DUST EMISSION FROM YOUNG STARS

Hill et al. (2005) made 1.2-mm dust continuum observations of a sample of 131 high-mass star formation regions, identified on the basis of either the presence of an UCH II region, or a 6.7-GHz methanol maser. Similar to Urquhart et al., Hill et al. found a small fraction of their targets (20 methanol masers and nine UCH II regions) for which they did not detect dust continuum emission. At the 3σ sensitivity of their observations, Hill et al. were sensitive to all sources with a dust mass in excess of 600 $\mathrm{M}_\odot$ at distances of 16.3 kpc or less (i.e. over the vast majority of the region of the Galaxy where high-mass star formation is present). Since the majority of the dust sources they detected have masses in excess of their sensitivity limit, they suggest three possible explanations for the 29 non-detections: (1) these sources have characteristics dissimilar to the majority of high-mass star formation regions; (2) that these sources are associated with later stages of star formation; or (3) these sources are located at too great a distance and are not massive enough to be detectable.

At least two of the nine UCH II regions for which Hill et al. (2005) find no accompanying dust continuum emission have been extensively studied (e.g. G 188.770+1.074 and G 23.43–0.18; Kurtz, Churchwell & Wood 1994; Walsh et al. 1998; Kim & Koo 2001; Trinidad & Rodríguez 2010) and their UCH II region nature is irrefutable. Both of these sources are located in complexes which contain methanol masers with distances measured through trigonometric parallax observations (G 188.95+0.89 and G 23.44–0.18; Reid et al. 2009). G 188.770+1.074 and G 23.43–0.18 are located at 2.10 and 5.88 kpc (Reid et al. 2009), respectively, meaning that the Hill et al. (2005) observations are not sensitivity limited. This clearly demonstrates that some high-mass star formation regions have unusually low dust masses, by the evolutionary phase when UCH II regions and 6.7-GHz methanol masers are present. Thus, the absence of dust emission associated with a methanol maser is not itself sufficient to suggest an origin other than a high-mass star formation region.

4 G 328.385+0.131 AND G 10.10+0.73 – ASSOCIATED WITH EVOLVED STARS?

We have investigated the two maser sources for which an association with an evolved star has been proposed (Walsh et al. 2003; Urquhart et al. 2013). The results of our investigation of G 328.385+0.131 are given in detail in Section 4.1. The case of G 10.10+0.73 can be simply dismissed as a spurious detection as discussed in Section 4.2. Here we summarize the key arguments which clearly show that there is no basis to the proposition that G 328.385+0.131 is associated with an evolved star.

(i) The classification of G 328.385+0.131 by Robitaille et al. (2008) as a possible AGB star is likely erroneous. The source is most probably a luminous YSO which their mid-infrared colour–magnitude criteria misclassified.

(ii) The infrared properties of G 328.385+0.131 are in the middle of the range seen for large samples of methanol masers. We further find the point-like nature of the associated 8.0-μm emission to be fairly common for sources associated with methanol masers.

(iii) The methanol maser at G 328.385+0.131 has a high luminosity. If such a luminous maser were associated with an evolved star we would expect to see other examples within the Galaxy.

(iv) We find a convincing $\sim 3\sigma$ 870-μm detection (∼320 mJy) at G 328.385+0.131 in the ATLASGAL data, contrary to the non-detection reported by Urquhart et al. (2013), which surpasses the flux density possible from any AGB star.

(v) The mass of the dust associated with G 328.385+0.131 is ∼600 $\mathrm{M}_\odot$ which is consistent with other regions that support high-mass star formation.

4.1 Methanol maser G 328.385+0.131

4.1.1 Infrared characteristics

The possible AGB star designation assigned to G 328.385+0.131 by Robitaille et al. (2008) was determined from a set of criteria they derived for the separation of YSOs and AGB stars. Robitaille et al. (2008) classify sources with $[4.5] \le 7.8$ as 'extreme' AGB star candidates, but note that this criterion will also capture a number of luminous YSOs. In the case where $[4.5] > 7.8$ there are two further criteria: if $[8.0] - [24.0] < 2.5$ they classify the source as a 'standard' AGB star, and if $[8.0] - [24.0] \ge 2.5$ they classify the source as a YSO. Examining the relevant colours and magnitudes of G 328.385+0.131, it is clear that it barely makes it into the possible AGB category on the first criterion, with $[4.5] = 7.68$ (in fact, this value is only 3.2σ from the 4.8 μm magnitude threshold of 7.8). If this source had a slightly higher magnitude, it would be classified as a YSO as it satisfies the second criterion ($[8.0] - [24.0] = 3.5$). It is therefore likely that this source is one of the luminous YSOs that has been wrongly classified as an AGB star, which, as Robitaille et al. (2008) mentioned, was inevitable.

Gallaway et al. (2013) used an adaptive non-circular aperture photometry technique to determine the GLIMPSE fluxes for sources associated with the methanol masers detected in the Methanol Multibeam Survey (a survey for methanol maser emission in the Galactic Plane; Green et al. 2009). Their table 1 lists 4.5-μm magnitudes towards 444 methanol masers, a large fraction of which (35 per cent) have $[4.5] \le 7.8$ and would therefore also be classified as 'extreme' AGB stars by the Robitaille et al. (2008) criteria. It is clearly unreasonable to expect such a large fraction of methanol masers to be associated with AGB stars, when an alternative explanation exists in which these are instead the expected fraction of YSOs that are inevitably captured by the simplistic colour–magnitude criteria (Robitaille et al. 2008). This highlights the difficulties in relying upon infrared selection criteria alone to classify individual sources. Furthermore, looking more closely at the IRAC colours of the mid-infrared counterpart of G 328.385+0.131, it is evident that this source lies in the middle of the range of colour–colour and colour–magnitude plots of sources associated with methanol masers (Ellingsen 2006; Breen et al. 2011; Gallaway et al. 2013) adding further support to the argument that this source is actually a standard high-mass star formation region.

In their study of the GLIMPSE properties of sources associated with 6.7-GHz methanol masers, Gallaway et al. (2013) also found that of their 769 methanol masers, 219 (28 per cent) were well characterized by a point source in all four IRAC bands. Since this is the case, the point-like nature of the infrared source associated with G 328.385+0.131 does not indicate that the emission is associated with an AGB star, as suggested by Urquhart et al. (2013).

4.1.2 Distance, maser luminosity and association with other lines

Our ability to confidently estimate the distance of G 328.385+0.131 is dependent on the nature of the source: if it is a high-mass star formation region it is necessarily constrained to the spiral arms and the velocity of the methanol maser emission will follow that of Galactic rotation (6.7-GHz methanol masers typically show their median velocity within 3–5 km s^{-1} of the systemic velocity of the region; Szymczak, Bartkiewicz & Richards 2007; Pandian, Menten & Goldsmith 2009; Green & McClure-Griffiths 2011), making kinematic distance determination viable; if, on the other hand, the source is an AGB star, the range of expected velocities is not restricted to Galactic rotation and kinematic distance determination is subject to much greater uncertainty.

We have inspected the CO emission from the NANTEN Galactic Plane Survey (Mizuno & Fukui 2004) and find an isolated spectral feature in the CO spectrum that matches the velocity of the methanol maser emission (see Fig. 1). The spectral structure of the detected CO emission is unlike typical AGB CO spectra (e.g. Castro-Carrizo et al. 2010) which tend to be broad (Full Width at Half Maximum > 20 km s^{-1}), flat-topped and steep-edged (i.e. more like a top-hat than a Gaussian profile). Crucially, if the CO was associated with an AGB of an anomalous velocity we would expect to see the CO emission restricted only to the immediate spatial vicinity of the AGB star. Castro-Carrizo et al. (2010) measured the CO properties of a representative sample of AGB and post-AGB stars, finding that the (1–0) emission was extended by no more than ∼40 arcsec for sources at distances up to 1 kpc. The NANTEN survey was observed in a 4 arcmin grid and the CO emission presented in Fig. 1 extends to at least two positions adjacent to G 328.400+0.133, corresponding to a structure of CO covering at least 8 arcmin. Such a large structure is wholly inconsistent with the CO emission expected for any AGB star, even one that is very close by. Conversely, such a CO structure is completely consistent with the extended emission seen within the spiral arms of our Galaxy, further confirmed by the velocity of the emission, which matches that of the Carina–Sagittarius spiral arm at this Galactic longitude.

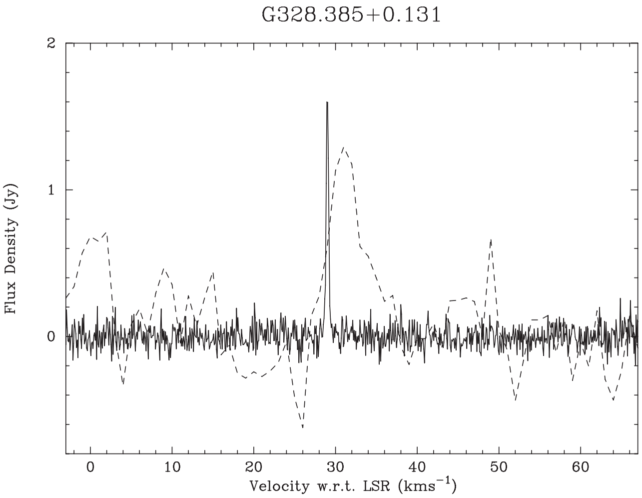

Figure 1. The methanol maser G 328.385+0.131 (Green et al. 2012a) overlaid with the CO emission (a 6.8σ detection) from the nearest pixel of the NANTEN data (position G 328.400+0.133). Note that the CO spectrum has the units of K, but the same scale as the methanol maser.

Given the tendency of methanol masers to trace the systemic velocities of the regions they are associated with, the well-matched velocities of the methanol and CO emission, together with the expected velocity of the Carina–Sagittarius spiral arm at this longitude and the low latitude of the source, it is most likely that the methanol maser is associated with CO following Galactic rotation. Thus, the positive velocity of the methanol maser at 28.9 km s^{-1} (Green et al. 2012a) undoubtedly places it at the far kinematic distance, in agreement with the distance assigned by Urquhart et al. of 18.0 kpc. We further note the presence of nearby luminous SNR 328.4+0.2, which is located at a similar distance [16.8 kpc: Caswell et al. (1975); 17.4 ± 0.9 kpc: Gaensler, Dickel & Green (2000)], illustrating that this part of the Galaxy is clearly capable of supporting high-mass star formation; in fact, the Galactic longitude versus velocity diagram presented in Green et al. (2012a) shows that there are several other methanol masers with similar Galactic longitudes and velocities.

The detected CO emission implies an H_2 mass of $\sim$5300 M$_\odot$ (assuming a solar-neighbourhood Galactic X-factor of 1.8×10^{20}; Dame, Hartmann & Thaddeus 2001, and a distance of 18 kpc) in a single NANTEN position, or a total cloud mass of $\sim 10^4$ M$_\odot$ (over the three adjacent positions where CO at this velocity was detected). The estimated mass of the molecular gas is also consistent with the cloud being located within the spiral arms of our Galaxy.

The association of the methanol maser with the corotating gas within the spiral arms of our Galaxy does not alone definitively suggest either an AGB or high-mass star formation origin. However, the strong likelihood of a far kinematic distance (∼18 kpc) is key to arguments made later in this section and those in Section 4.1.3.

The methanol maser emission associated with G 328.385+0.131 was reported by Green et al. (2012a) to consist of a single spectral feature with a peak flux density of 1.6 Jy, and appeared stable over the course of the initial MMB survey and follow up observations. While this is a relatively modest flux density, its distance at 18 kpc places it in the upper middle of the luminosity range of all 366 MMB sources presented in fig. 7 of Breen et al. (2011). If an AGB star were capable of producing such a luminous methanol maser, we would expect to detect further sources of this type within the Galaxy, but we do not. Comparison between a large fraction of the full complement of 6.7-GHz methanol masers in the Southern hemisphere and mid-infrared data led Gallaway et al. (2013) to reconfirm that these masers are exclusively associated with high-mass star formation. If there were a significant population of methanol masers associated with evolved stars, it would be expected that the Gallaway et al. (2013) study (and other earlier studies) would have uncovered it.

No further indications of the source's nature can be derived from the targeted 12.2-GHz methanol maser observations conducted by Breen et al. (2012b), which revealed no emission at 5σ levels of 0.75 and 0.8 Jy during 2008 June and December, respectively. The 12.2-GHz methanol maser catalogues of Breen et al. (2012a,b) show that in the Galactic longitude range 186 to 330° approximately 44 per cent of 6.7-GHz methanol masers have 12.2-GHz counterparts (commonly with 6.7-GHz to 12.2-GHz peak flux density ratios greater than 2:1).

We have inspected the water maser (Walsh et al. 2011) and ammonia data (Purcell et al. 2012) from the H_2O Southern Galactic

Plane Survey (HOPS) and find no detection of either tracer. The modest sensitivity of this survey (98 per cent complete at 8.4 Jy for water masers and 100 per cent complete at $T_{mb} = 1.0$ K for ammonia) combined with the outer Galactic distance for this source preclude us from drawing any conclusions from these data. Recent observations for OH masers in the 1612-, 1665-, 1667- and 1720-MHz lines have been carried out as part of MAGMO (a project to study the Magnetic fields of the Milky Way through OH masers; Green et al. 2012b) towards this source and made no detections in any of the OH transitions to a 5σ detection limit of ∼250 mJy.

4.1.3 The dust emission

Using ATLASGAL data, Urquhart et al. (2013) report that there is no 870-µm emission at the location of the methanol maser to an upper limit of 320 mJy. We have inspected the image provided by Urquhart et al., which shows the mid-infrared environment associated with G 328.385+0.131 overlaid with ATLASGAL contours. This image shows unresolved emission at a 3-σ level (signified by the presence of three 1σ interval contours) towards the location of the methanol maser. Given the coincidence of the dust emission with the methanol maser, and the absence of any further emission beyond a 1σ level in the region surrounding the methanol maser, we believe this to be an authentic dust continuum detection. We therefore reinterpret the Urquhart et al. upper limit of 320 mJy to be a detection at about this flux density and similarly the presented dust mass upper limit of 579.17 $\mathrm{M_\odot}$ beam^{-1} to be the estimated dust mass of the detected source.

Urquhart et al. find that 28 per cent of dust sources with methanol masers have calculated dust masses of less than 1000 $\mathrm{M_\odot}$. They suggest that the majority of these are more compact (in most cases <0.3 pc) and may have higher star formation efficiency and be forming smaller-stellar-mass systems. From fig. 15 of Urquhart et al., it seems that all of their sources with masses greater than about 100 $\mathrm{M_\odot}$ fall in the high-mass star-forming range of values satisfying the Kauffmann et al. (2010a,b) criteria. There is therefore no evidence to suggest that G 328.385+0.131, with a mass of ∼550 $\mathrm{M_\odot}$ beam^{-1}, would be unable to support high-mass star formation. Furthermore, Urquhart et al. apply a constant temperature of 20 K to all of their sources. While this is a reasonable average for many young star formation regions, individual sources may vary by several K from this value which significantly impacts the derived mass [e.g. if the temperature was actually 15 K, as can often be the case (e.g. Carey et al. 2000), the mass would increase by 58 per cent].

Conversely, the likelihood that an AGB star would be detectable at such a far distance in the 870-µm ATLASGAL data seems unlikely. To consider if this is possible, we have calculated the expected 870-µm emission from an AGB star located at 18 kpc. The flux density of the dust envelope of an AGB star at 870-µm, assuming that the dust continuum emission is optically thin, is given by (Hildebrand 1983):

$$F_{870} = 1.05 \times 10^{36} \frac{M_d \kappa_{870} B_{870}(T_d)}{D^2},$$

where M_d is the AGB envelope mass, κ_{870} is the dust opacity coefficient, $B_{870}(T_d)$ is the Planck function at the dust temperature (erg s^{-1} cm^{-3}), and D is the distance (pc).

The dust opacity at 870-µm has an estimated value of 1.87 cm^2 g^{-1} for ATLASGAL observations (Schuller et al. 2009); however, towards circumstellar grains it can vary by up to an order of magnitude (Sopka et al. 1985). Ladjal et al. (2010) conducted 870-µm observations towards nine evolved stars and found values of dust opacity ranging from 2 to 35 cm^2 g^{-1}. We therefore calculate limits on the expected flux density using these two extreme values.

Assuming a dust temperature of 1000 K (estimated from observations of nearby AGB stars; Ladjal et al. 2010), together with their average dust envelope mass of $\sim 2 \times 10^{-3}$ $\mathrm{M_\odot}$, the expected flux densities for each of the two extreme dust opacity values are:

$$F_{870} = \begin{cases} 9\,\mathrm{mJy} & (\text{for } \kappa_{870} = 2\ \mathrm{cm^2\ g^{-1}}) \\ 160\,\mathrm{mJy} & (\text{for } \kappa_{870} = 35\ \mathrm{cm^2\ g^{-1}}) \end{cases},$$

making it is very unlikely that 870-µm emission would be any stronger than 160 mJy and quite likely considerably less given a more reasonable value of dust opacity. Since the flux density of the 3σ 870-µm emission associated with the methanol maser is ∼320 mJy, it is highly probable that we can rule out that the origin of this emission is an AGB star.

4.1.4 SED modelling

We have used the online spectral energy distribution (SED) fitting tool of Robitaille et al. (2007) to investigate the nature of the emission associated with G 328.385+0.131. We allowed the fitting distance to vary between 16 and 18 kpc. The resultant SED fit is presented in Fig. 2, and shows the characteristics of a deeply embedded, high-luminosity YSO. Using the criterion of Carlson et al. (2011), we were able to confirm that there was no significant PAH emission, which is not accounted for in the YSO models used in the SED fitting (Robitaille et al. 2006).

Pandian et al. (2010) investigated the SEDs of the centimetre through to near-infrared emission associated with 20 6.7-GHz methanol masers which comprise a complete sample of methanol masers between Galactic longitudes 38°.6 and 43°.1, and latitudes $|b| \leq 0°.42$. The fitted characteristics of G 328.385+0.131 (derived from the best-fitting model shown in Fig. 2) all fall within the range of those derived for the Pandian et al. sample. The only exception is the source age which is about twice that of the oldest sources given in their study. The significance of this difference is unlikely to be

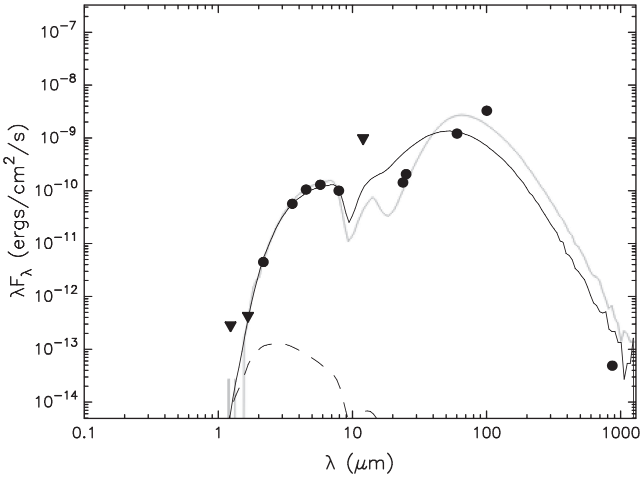

Figure 2. The SED and fitted YSO models for G 328.385+0.131. The dots and the triangles are measurements and upper limits taken from (left to right) the 2MASS (3), GLIMPSE (4), *IRAS* (1), MIPSGAL (1; Robitaille et al. 2008), *IRAS* (3) and ATLASGAL (1) surveys. The solid black line shows the best-fitting model, the solid grey line gives the second best-fitting model, while the dashed line gives the spectrum of the stellar photosphere in the absence of circumstellar dust but accounting for interstellar extinction.

high given the size of their sample, together with the range of their values (1.2 to 57 × 10^3 yr cf. 110 × 10^3 yr for G 328.385+0.131).

Robitaille et al. (2008) present a sample of SEDs for both their standard AGB and YSO candidates. Although some of the 'extreme' AGB candidates presented in Robitaille et al. (2008) have SEDs that are more comparable to that of YSOs, the standard AGB candidates have very different characteristics than those of G 328.385+0.131 shown in Fig. 2. In each of the 18 standard AGB cases presented in Robitaille et al. (2008), the SED falls significantly beyond wavelengths of 5.8 μm (and sometimes from even shorter wavelengths), a property not shared by the data presented for G 328.385+0.131 which is well fitted by a YSO model.

4.2 Methanol maser G 10.10+0.73

Walsh et al. (1998) conducted ATCA observations of methanol masers detected towards *IRAS* sources (Walsh et al. 1997) in order to derive precise source positions. The methanol maser observed by Walsh et al. (1998) in the target field of *IRAS* source 18021−1950 was found to be significantly offset from the target *IRAS* source (by 116.79 arcsec in RA and –38.46 arcsec in declination) and was detected as a single feature of 1.2 Jy at a velocity of 1.2 km s^{-1}. The location of this methanol maser was found to have no coincident dust continuum emission (Walsh et al. 2003) and, combined with its proximity to planetary nebula NGC 6537, led to the suggestion of a possible association between the two objects.

This methanol maser was not detected in the complete MMB survey (Green et al. 2010), perhaps not too surprising given the intrinsically variable nature of masers and the 5σ sensitivity of the survey observations, which at 0.7 Jy is not greatly different from the flux density of the Walsh et al. (1998) detection. Although the non-detection in the Green et al. (2010) observation is not suspicious alone, the reported maser is, notably, less than a degree from the strongest methanol maser in the Galaxy, G 9.621+0.196, with velocity of 1.3 km s^{-1} and emission regularly detected with a peak flux density in excess of 5000 Jy (e.g. Green et al. 2010), and this prompted us to download and inspect the data used in Walsh et al. (1998) from the Australia Telescope Online Archive (ATOA).

The ATCA data were taken on 1994 July 30 and consisted of four cuts of two minutes each, spread over almost 8 h. Observations of PKS B1934–638 were made for primary flux density and bandpass calibration, and 1808–209 for gain calibration (which had a flux density of ∼0.25 Jy at the time of the observations). For these observations the correlator was set to record 1024 channels over a bandwidth of 4-MHz, yielding a channel spacing of 0.18 km s^{-1} and a coverage of 180 km s^{-1} (Walsh et al. 1998).

Despite several attempts using MIRIAD, employing standard data reduction techniques for ATCA spectral line data, we have been unable to reproduce the 1.2 Jy detection from the same ATCA data. We suggest that the reported detection is most likely an image artefact arising from the nearby bright emission of G 9.621+0.196 which was more pronounced than usual because the quality of the data was inadequate to form reliable images (in particular, the phase calibrator was too weak for the correlator configuration and system available at the time of the observations) and possibly further due to inferior data reduction algorithms available almost 20 years ago.

We conclude that the reported methanol maser G 10.10+0.73 detected at a velocity of 1.2 km s^{-1} is not an authentic maser detection and therefore has no possibility of supporting the suggestion that methanol masers can be associated with evolved stars as suggested in both Walsh et al. (2003) and Urquhart et al. (2013).

5 CONCLUSION

We have investigated the suspected association between two 6.7-GHz methanol masers, G 328.385+0.131 and G 10.10+0.73, with evolved stars (Walsh et al. 2003; Urquhart et al. 2013). We find no evidence to support these claims, rather finding G 328.385+0.131 to be an average methanol-maser-associated YSO, and G 10.10+0.73 to be a spurious source caused by the strong emission from nearby methanol maser G 9.621+0.196.

More generally, we argue that it is unlikely that the environments of evolved stars contain a high enough abundance of methanol to support maser emission. We therefore confirm that the exclusive association of 6.7-GHz methanol masers with star formation regions remains valid.

ACKNOWLEDGEMENTS

We thank the referee, Anita Richards, for insightful and thorough comments that allowed us to significantly improve the quality of the paper. This research has made use of: NASA's Astrophysics Data System Abstract Service; the NASA/ IPAC Infrared Science Archive (which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration); the SIMBAD data base, operated at CDS, Strasbourg, France; and data products from the GLIMPSE and MIPSGAL surveys, which are legacy science programs of the *Spitzer Space Telescope*, funded by the National Aeronautics and Space Administration.

REFERENCES

Aguirre J. E. et al., 2011, ApJS, 192, 4
Bourke T. L., Hyland A. R., Robinson G., 2005, ApJ, 625, 883
Breen S. L., Ellingsen S. P., Caswell J. L., Green J. A., Fuller G. A., Voronkov M. A., Quinn L. J., Avison A., 2011, ApJ, 733, 80
Breen S. L., Ellingsen S. P., Caswell J. L., Green J. A., Fuller G. A., Voronkov M. A., Quinn L. J., Avison A., 2012a, MNRAS, 421, 1703
Breen S. L., Ellingsen S. P., Caswell J. L., Green J. A., Fuller G. A., Voronkov M. A., Quinn L. J., Avison A., 2012b, MNRAS, 426, 2189
Carey S. J., Feldman P. A., Redman R. O., Egan M. P., MacLeod J. M., Price S. D., 2000, ApJ, 543, L157
Carlson L. R. et al., 2011, ApJ, 730, 78
Castro-Carrizo A. et al., 2010, A&A, 523, 59
Caswell J. L., Murray J. D., Roger R. S. Cole D. J., Cooke D. J., 1975, A&A, 45, 239
Caswell J. L. et al., 2010, MNRAS, 404, 1029
Caswell J. L. et al., 2011, MNRAS, 417, 1964
Contreras Y. et al., 2013, A&A, 549, A45
Cragg D. M., Sobolev A. M., Godfrey P. D., 2002, MNRAS, 331, 521
Cragg D. M., Sobolev A. M., Godfrey P. D., 2005, MNRAS, 360, 533
Cyganowski C. J., Brogan C. L., Hunter T. R., Churchwell E., 2009, ApJ, 702, 1615
Dame T. M., Hartmann D., Thaddeus P., 2001, ApJ, 547, 792
Dartois E., Schutte W., Geballe T. R., Demyk K., Ehrenfreund P., D'Hendecourt L., 1999, A&A, 342, L32
Deguchi S., 2007, in Chapman J. M., Baan W. A., eds, Proc. IAU Symp., 242, Astrophysical Masers and their Environments. Cambridge Univ. Press, Cambridge, p. 200
Desmurs J.-F., Baudry A., Sivagnanam P., Henkel C., Richards A. M. S., Bains I., 2010, A&A, 520, 45
Ellingsen S. P., 2006, ApJ, 638, 241
Ford K. E. S., Neufeld D. A., Schilke P., Melnick G. J., 2004, ApJ, 614, 990
Gaensler B. M., Dickel J. R., Green A. J., 2000, ApJ, 542, 380
Gallaway M. et al., 2013, MNRAS, 430, 808

Garrod R., Park I. H., Caselli P., Herbst E., 2006, Faraday Discussions, 133, 51
Gibb A. G., Davis C. J., 1998, MNRAS, 298, 644
Gibb E. L., Whittet D. C. B., Boogert A. C. A., Tielens A. G. G. M., 2004, ApJS, 151, 35
Goddi C., Moscadelli L., Sanna A., 2011, A&A, 535, 8
Green J. A., McClure-Griffiths N., 2011, MNRAS, 417, 2500
Green J. A. et al., 2009, MNRAS, 392, 783
Green J. A. et al., 2010, MNRAS, 409, 913
Green J. A. et al., 2012a, MNRAS, 420, 3108
Green J. A., McClure-Griffiths N. M., Caswell J. L., Robishaw T., Harvey-Smith L., 2012b, MNRAS, 425, 2530
He J. H., Dinh-V-Trung, Kwok S., Müller H. S. P., Zhang Y., Hasegawa T., Peng T. C., Huang Y. C., 2008, ApJS, 177, 275
Hildebrand R. H., 1983, QJRAS, 24, 267
Hill T., Burton M. G., Minier V., Thompson M. A., Walsh A. J., Hunt-Cunningham M., Garay G., 2005, MNRAS, 363, 405
Hudson R. L., Moore M. H., 1999, Icarus, 140, 451
Kalenskii S. V., Johansson L. E. B., Bergman P., Kurtz S., Hofner P., Walmsley C. M., Slysh V. I., 2010, MNRAS, 405, 613
Kauffmann J., Pillai T., Shetty R., Myers P. C., Goodman A. A., 2010a, ApJ, 712, 1137
Kauffmann J., Pillai T., Shetty R., Myers P. C., Goodman A. A., 2010b, ApJ, 716, 433
Kim K.-T., Koo B.-C., 2001, ApJ, 549, 979
Kurtz S., Churchwell E., Wood D. O. S., 1994, ApJ, 91, 659
Ladjal D., Justtanont K., Groenewegen M. A. T., Blommaert J. A. D. L., Waelkens C., Barlow M. J., 2010, A&A, 513, A53
Menten K. M., 1991a, in Haschick A., Ho P. T. P., eds, ASP Conf. Ser. Atoms, Ions and Molecules: New Results in Spectral Line Astrophysics. Astron. Soc. Pac., San Francisco, p. 119
Menten K. M., 1991b, ApJ, 380, L75
Minier V., Booth R. S., Conway J. E., 1998, A&A, 336, 5
Minier V., Booth R. S., Conway J. E., 2000, A&A, 362, 1093
Minier V., Ellingsen S. P., Norris R. P., Booth R. S., 2003, A&A, 403, 1095
Mizuno A., Fukui Y., 2004, in Clemens D., Shah R., Brainerd T., eds, ASP Conf. Ser. Vol. 317, Milky Way Surveys: The Structure and Evolution of our Galaxy. Astron. Soc. Pac., San Francisco, p. 59
Pandian J. D., Menten K. M., Goldsmith P. F., 2009, ApJ, 706, 1609
Pandian J. D., Momjian E., Xu Y., Menten K. M., Goldsmith P. F., 2010, A&A, 522, A8
Pontoppidan K. M., van Dishoeck E. F., Dartois E., 2004, A&A, 426, 925
Purcell C. R. et al., 2012, MNRAS, 426, 1972
Reid M. J. et al., 2009, ApJ, 700, 137
Robitaille T. P., Whitney B. A., Indebetouw R., Wood K., Denzmore P., 2006, ApJS, 167, 256
Robitaille T. P., Whitney B. A., Indebetouw R., Wood K., 2007, ApJS, 169, 328
Robitaille T. P. et al., 2008, AJ, 136, 2413
Sahai R., Nyman L.-Å., 1997, ApJ, 487, L155
Schuller F. et al., 2009, A&A, 504, 415
Sevenster M. N., Chapman J. M., Habing H. J., Killeen N. E. B., Lindqvist M., 1997a, A&AS, 122, 79
Sevenster M. N., Chapman J. M., Habing H. J., Killeen N. E. B., Lindqvist M., 1997b, A&AS, 124, 509
Sevenster M. N., van Langevelde H. J., Moody R. A., Chapman J. M., Habing H. J., Killeen N. E. B., 2001, A&A, 366, 481
Sopka R. J., Hildebrand R., Jaffe D. T., Gatley I., Roellig T., Werner M., Jura M., Zuckerman B., 1985, ApJ, 294, 242
Szymczak M., Bartkiewicz A., Richards A. M. S., 2007, A&A, 468, 617
Taquet V., Peters P. S., Kahane C., Ceccarelli C., López-Sepulcre A., Toubin C., Duflot D., Wiesenfeld L., 2013, A&A, 550, A127
Tielens A. G. G. M., Whittet D. C. B., 1997, in van Dishoeck E. F., ed., IAU Symp. 178, Molecules in Astrophysics: Probes & Processes. Kluwer, Dordrecht, p. 45
Trinidad M. A., Rodríguez T., 2010, AJ, 140, 1739
Urquhart J. S. et al., 2013, MNRAS, 431, 1752
Walsh A. J., Hyland A. R., Robinson G., Burton M. G., 1997, MNRAS, 291, 261
Walsh A. J., Burton M. G., Hyland A. R., Robinson G., 1998, MNRAS, 301, 640
Walsh A. J., Macdonald G. H., Alvey N. D. S., Burton M. G., Lee J.-K., 2003, A&A, 410, 597
Walsh A. J. et al., 2011, MNRAS, 416, 1764
Xu Y., Li J. J., Hachisuka K., Pandian J. D., Menten K. M., Henkel C., 2008, A&A, 485, 729
Yusef-Zadeh F., Cotton W., Viti S., Wardle M., Royster M., 2013, ApJ, 764, 19

This paper has been typeset from a TEX/LATEX file prepared by the author.

Log in to My Ulrich's

Macquarie University Library --Select Language--

Search Workspace Ulrich's Update Admin

Enter a Title, ISSN, or search term to find journals or other periodicals:

0035-8711

Advanced Search

Search My Library's Catalog: ISSN Search | Title Search

Search Results

Royal Astronomical Society. Monthly Notices

Title Details Table of Contents

Related Titles

- **Alternative Media Edition** (2)
- **Supplement** (1)

Lists

Marked Titles (0)

Search History

0035-8711 - (1)

Save to List Email Download Print Corrections Expand All Collapse All

Basic Description

Title	Royal Astronomical Society. Monthly Notices
ISSN	0035-8711
Publisher	Oxford University Press
Country	United Kingdom
Status	Active
Start Year	1827
Frequency	36 times a year
Language of Text	Text in: English
Refereed	Yes
Abstracted / Indexed	Yes
Serial Type	Journal
Content Type	Academic / Scholarly
Format	Print
Website	http://www.oxfordjournals.org/our_journals/mnras/
Description	Publishes the results of original research in positional and dynamical astronomy, astrophysics, radio astronomy, cosmology, space research and the design of astronomical instruments.

- **Subject Classifications**
- **Additional Title Details**
- **Title History Details**
- **Publisher & Ordering Details**
- **Price Data**
- **Online Availability**
- **Abstracting & Indexing**
- **Other Availability**
- **Demographics**
- **Reviews**

Save to List Email Download Print Corrections Expand All Collapse All