Circumstellar masers in the Magellanic Clouds

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ABSTRACT

The nearby dwarf irregular galaxies the Large and Small Magellanic Clouds have metallicities of about half and a fifth solar, respectively, which offers the unique opportunity to study astrophysical processes as a function of metallicity. Masers in the outflows from evolved stars allow to measure the wind speed, vital to derive mass-loss rates and test wind driving mechanisms. The metallicity dependence of the wind speed in particular allows us to make inferences about dust formation and mass loss in the early Universe. I will review past surveys for circumstellar OH, water, and SiO masers in the Magellanic Clouds (and provide a literature review of interstellar masers). I will then discuss the way these measurements have influenced our understanding of mass loss, and end with outlining the prospects for future surveys for OH masers in the Magellanic Clouds.

Subject headings: masers — stars: AGB and post-AGB — stars: mass-loss — supergiants — stars: winds, outflows — Magellanic Clouds

1. The astrophysical significance of masers in the Magellanic Clouds

Microwave amplified stimulated emission radiation (maser) arises when emission from a transition within a molecule is amplified when it causes subsequent stimulated emission from the same transition within another such molecule. For this to happen, a population inversion needs to be instated, so the meta-stable higher energy level of the masing transition becomes populated preferentially over the energy level to which it decays. The mechanism responsible for this "pumping" can be either through the absorption of radiation in transitions to levels from which the upper level of the masing transition can be populated, or through collisions with other particles. Masers therefore require specific conditions to be met; conversely, the radiation is highly an-isotropic.

The result is extremely bright emission linked to specific regions and kinematics in the object (Elitzur, Goldreich, & Scoville 1976; Chapman & Cohen 1986). In the outflows of cool evolved star winds – Asymptotic Giant Branch (AGB) stars or red supergiants – prototypical hydroxyl (OH) masers display a double-horned profile separated by twice the wind speed; water (H_2O) masers probe accelerating parts of the wind near the dust formation zône; while silicon-monoxide (SiO) masers tend to peak near the stellar systemic velocity. The detection of masers in these objects thus allows the measurement of the gas kinematics in the outflow, which informs us about its driving mechanism – believed to be due to radiation pressure on dust grains – and about the grain properties. In star forming regions, methanol (CH_3OH) masers play a valuable rôle in locating warm cores.

The Magellanic Clouds offer us unique laboratories for studying astrophysical processes due to their proximity (about 50 and 60 kpc for the Large and Small Magellanic Clouds, respectively), different metal content (half and a fifth solar, for respectively the LMC and SMC), and decent size and on-going star formation resulting in sufficient examples of the intrinsically rare stages during which masers are observed.

2. The known circumstellar masers in the Magellanic Clouds

I have listed in Table 1 an overview of the literature on circumstellar masers in the Magellanic Clouds – i.e. masers in the outflows from cool evolved stars. Not only have there been few publications, the number of detected masers (10) is so small that I can list them all (Table 2, along with a few candidates based on their similar spectral types, pulsation periods and dust envelopes). To date, no circumstellar masers are known in the SMC. For the sake of this review I consider all other masers to be of "interstellar" origin, and only provide a list of references in relation to their detection in the Magellanic Clouds (Table 3).

Few circumstellar masers have been detected due to their faintness as well as difficulties with the target selection. Targets were selected predominantly from the IRAS point source catalogue, but many of the targets selected for the first study by Wood et al. (1992) later turned out to be carbon stars – which do not display masers – or not cool evolved stars at all, resulting in their low success rate of 6 out of 54. The second search, with the ATCA (van Loon et al. 1998a) targetted two objects, one of which was detected (IRAS 04407−7000) while the other was a carbon star after all. The third systematic survey, presented in

Table 1: Literature on circumstellar masers in the Magellanic Clouds.

year	authors	telescope	molecule	remarks
1986	Wood et al.	Parkes	OH	first detection
1992	Wood et al.	ATCA+Parkes	OH	
1996	van Loon et al.	SEST	SiO	first detection
1998a	van Loon et al.	ATCA	OH	
1998b	van Loon et al.	Parkes	H_2O	first detection
2001b	van Loon et al.	Mopra+Parkes+SEST	H_2O + SiO	
2004	Marshall et al.	Parkes	OH	

Table 2: Circumstellar masers in the Magellanic Clouds including candidate OH/IR stars, with spectral type, pulsation period and OH peak intensity (r.m.s. noise in parentheses).

IRAS	other name	SpT	P (d)	OH peak (mJy)	remarks
Small Magellanic Cloud					
00483−7347		late-M	1859	(9)	
00486−7308	GM 103	M4	1062	?	
00591−7307	HV 11417	M5e I	1092	(8)	
Large Magellanic Cloud					
04407−7000		M7.5	1199	50	
04498−6842		M10	1292	23	
04509−6922		M10	1292	(17)	
04516−6902		M9	1091	(11)	
04545−7000			1216	140	
04553−6825	WOH G064	M7.5	841	600	H_2O, SiO
05003−6712		M9	883	33	
05280−6910	NGC 1984-IR1			90	H_2O
05294−7104		M8	1079	(13)	
05298−6957	HS 327E-IR1		1280	240	
05329−6708			1262	130	
05402−6956			1393	80	
05558−7000			1220	17	

Table 3: Literature on interstellar masers in the Magellanic Clouds.

year	authors	telescope	molecule	remarks
1977	Kaufmann et al.	Itapetinga	H_2O	no detection
1981	Caswell & Haynes	Parkes	OH	first detection
1981	Haynes & Caswell	Parkes	OH	
1981	Scalise & Braz	Itapetinga	H_2O	first detection
1982	Scalise & Braz	Itapetinga	H_2O	
1983	Whiteoak et al.	Parkes	H_2O	
1985	Gardner & Whiteoak	Parkes	OH	
1986	Whiteoak & Gardner	Parkes	H_2O	
1992	Sinclair et al.	Parkes	CH_3OH	first detection
1994	Ellingsen et al.	ATCA+Parkes	CH_3OH	
1995	Caswell	ATCA+Parkes	OH	excited OH
1996	Beasley et al.	ATCA	CH_3OH	
1997	Brooks & Whiteoak	ATCA	OH	
2001	van Loon & Zijlstra	Mopra	H_2O	
2002	Lazendić et al.	ATCA+Canberra	H_2O	
2004	Brogan et al.	ATCA	OH	supernova remnant
2005	Roberts & Yusef-Zadeh	ATCA	OH	supernova remnant
2006	Oliveira et al.	Parkes	H_2O	
2008	Green et al.	ATCA+Parkes	CH_3OH + OH	excited OH
2010	Ellingsen et al.	ATCA+Parkes	CH_3OH + H_2O	

Marshall et al. (2004), drew targets from the same pool of candidates but these had by then been much better characterised. OH/IR stars invariably have oxygen-rich dusty envelopes but also late-M spectral types and long pulsation periods reflecting their extremely evolved status. This selection yielded a 50 per cent success rate for the LMC targets, but it was evident that deeper searches would be needed to detect most of the candidates, and that some of the best candidates may still have escaped identification.

Of the detected maser sources (and some of the LMC candidates), pulsation periods were determined by Wood et al. (1992), dust chemical types by Trams et al. (1999), mass-loss rates by van Loon et al. (1999, 2005), and spectral types by van Loon et al. (1998a, 2005); their maser properties were summarised by Marshall et al. (2004). The SMC sources were characterised by Groenewegen & Blommaert (1998) with pulsation periods by Soszyński et al. (2011). Some sources are located in a star cluster, so we know the birth mass – due to mass loss the present-day mass will have diminished, which is partly reflected in the long pulsation period: IRAS 05280−6910 is a red supergiant evolved from a 19-$M_\odot$ main-sequence star (Wood et al. 1992; van Loon, Marshall, & Zijlstra 2005) while IRAS 05298−6957 used to be a 4-$M_\odot$ main-sequence star (van Loon et al. 2001a).

The extremely luminous and late-type dusty red supergiant IRAS 04553−6825 (WOH G064; cf. Elias, Frogel, & Schwering 1986) is the only OH/IR star in the Magellanic Clouds in which besides OH (Wood et al. 1986, 1992) – both the usual 1612 MHz satellite line as well as the 1665 and 1667 MHz main lines – also both H_2O (van Loon et al. 1998b) and SiO (van Loon et al. 1996) masers have been detected. Detection of the SiO maser revealed that what had originally been thought to be OH emission from the receding part of the circumstellar envelope actually is substructure in the approaching part of the envelope, the emission from the receding part was detected later and found to be much fainter (Marshall et al. 2004). This added to suspicions based on the spectral energy distribution –

bright infrared emission from dust but relatively little obscuration at optical wavelengths (Roche, Aitken, & Smith 1993; van Loon et al. 1999) – that the circumstellar envelope must resemble a torus or a shell with bipolar cavities, a conjecture which was beautifully confirmed with interferometric measurements by Ohnaka et al. (2008).

3. Testing radiation driven wind theory

There is strong empirical evidence for the mass-loss rates of cool evolved stars to depend very little on metal content but for the dust content of those outflows to scale approximately in proportion to metal content (Elias, Frogel, & Humphreys 1985; van Loon 2000; van Loon et al. 2008). Given this, simple prescriptions for radiation-driven dusty winds yield predictions for how the wind speed should depend on metal content and on luminosity (Habing, Tignon, & Tielens 1994; Elitzur & Ivezić 2001; Marshall et al. 2004):

$$v \propto \psi^{1/2} L^{1/4}, \tag{1}$$

where the dust:gas mass ratio $\psi \simeq 1 : 200$ at solar metallicity. This prediction was verified by comparing the measured wind speed as a function of luminosity in the LMC and in the Galactic Centre (Marshall et al. 2004).

There is a suggestion (Fig. 16 in Marshall et al. 2004) that the wind speed might in fact show a steeper dependence on luminosity in the LMC sample; this might be due to differences in the gravitational acceleration around the dust formation zône between stars of different masses and sizes, or possibly the dust fraction is higher for the more massive progenitor stars. The H_2O maser profiles of IRAS 04553−6825 and IRAS 05280−6910 clearly reveal the acceleration of the envelope, possibly at a slower rate than seen in Galactic objects (van Loon et al. 2001b). This could result from a lower dust content, with consequently a larger drift velocity between the dust grains and the gas fluid.

A similar discrepancy in parameter dependence was found by Marshall et al. (2004) between the mass-loss rates determined from the dust emission and those from the OH maser intensity following the recipe by Baud & Habing (1983) as presented by van der Veen & Rugers (1989); this suggests that the OH maser intensity may in fact measure the dust emission responsible for the maser pumping, rather than the gas mass (Zijlstra et al. 1996).

4. IRAS 05298−6957: a case study

IRAS 05298−6957 is the second-strongest OH maser source in the LMC, with the most "classic" maser profile, and also located in a star cluster. In Fig. 1 I plot its spectral energy distribution, with near-infrared photometry from van Loon et al. (2001a) and Wood et al. (1992), and 24- and 70-μm measurements obtained with the *Spitzer* Space Telescope (cf. van Loon et al. 2010). Overplotted is a 3000 K blackbody representing the central star (its effective temperature is not known but it is likely a late-M type star), and the spectral energy distribution resulting from radiation transfer through a dusty circumstellar envelope. The latter was computed using the DUSTY code (Nenkova, Ivezić, & Elitzur 2000), assuming a standard size distribution (Mathis, Nordsieck, & Rumpl 1977) of silicate grains (Draine & Lee 1984) that attain a temperature of 1000 K at the inner edge of the dust envelope. To match the measurements the computed model had to be scaled to a luminosity of 40 000 $L_\odot$ and, for a dust:gas mass ratio of 1:500, a mass-loss rate of 2×10^{-4} $M_\odot$ yr^{-1}.

At radio wavelengths, the brightness is dominated by the stellar photosphere, but the OH maser is more than a billion times (*sic* !) brighter, reaching similar levels as the peak of the spectral energy distribution at mid-infrared wavelengths (Fig. 1). The DUSTY model predicts a wind speed of 7.2 km s^{-1}, which is somewhat slower than the measured 10.5 km s^{-1} (Marshall et al. 2004). Possibly the grain properties are a little different or the dust:gas mass ratio is a little higher than assumed (raising it to $\psi \simeq 1 : 250$ would explain it). This exercise serves to demonstrate that measurement and modelling of the wind speed hold great promise to further our understanding of these dusty winds.

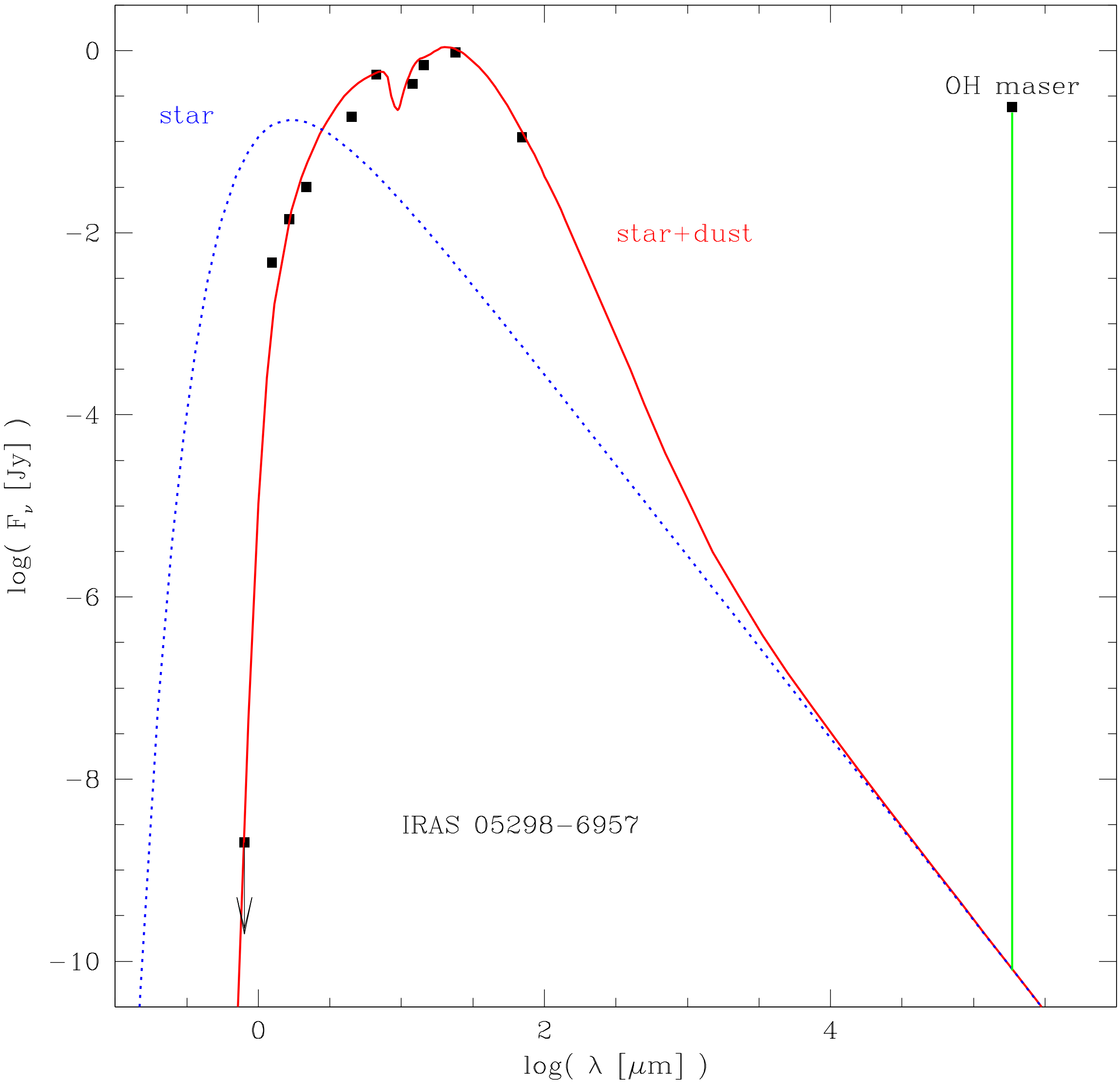

Fig. 1.— Spectral energy distribution of IRAS 05298−6957 including the OH maser.

5. Future prospects

The current best candidate OH/IR stars in both Magellanic Clouds (Table 2) very likely exhibit detectable OH emission not too far below the detection limits of past searches. Efforts are underway with Parkes and the ATCA to detect these. However, the IRAS survey was heavily confused in the Magellanic Clouds. Figs. 2 and 3 show the locations of the detected and candidate OH/IR stars on more recent *Spitzer* Space Telescope maps of the 24-μm emission, the wavelength where the relatively warm circumstellar dust emission peaks. Clearly, these sources are generally located in regions without strong diffuse emission from small interstellar grains. Especially red supergiant OH/IR stars would more often be found in dusty regions as they are not much older than the typical lifetime of the molecular cloud complexes in which they formed. Thus the *Spitzer* maps may harbour excellent targets, most of which await identification and characterisation.

The situation will improve dramatically with the advent of Square Kilometre Array (SKA) pathfinder experiments – viz. the Australian SKA Pathfinder (ASKAP) and Southern African MeerKAT arrays (van Loon, GASKAP Team & MagiKAT Team 2010). In particular the GASKAP survey combines high sensitivity (200-hr integrations) with large instantaneous synthesized field (30 square degrees) to reach the required survey speed and depth for a blind survey of the Magellanic Clouds, thus avoiding the need for pre-selection of targets. The synthesized beam of $< 20''$ greatly reduces the level of beam dilution and possible confusion at the low sensitivity that will be achieved (r.m.s. noise well below a mJy). Both the 1612 and 1665/1667 MHz transitions will be searched. Based on the detected masers in the LMC and Milky Way, and employing scaling relations of between the OH maser intensity and mid-infrared brightness, it is estimated that the GASKAP survey will uncover dozens of new OH/IR stars in the LMC (besides obtaining better quality data on the already known masers), and the first sample of OH/IR stars in the

SMC. Unprecedented tests of the driving of cool evolved star winds will become possible, especially with regard to its dependence on metal content.

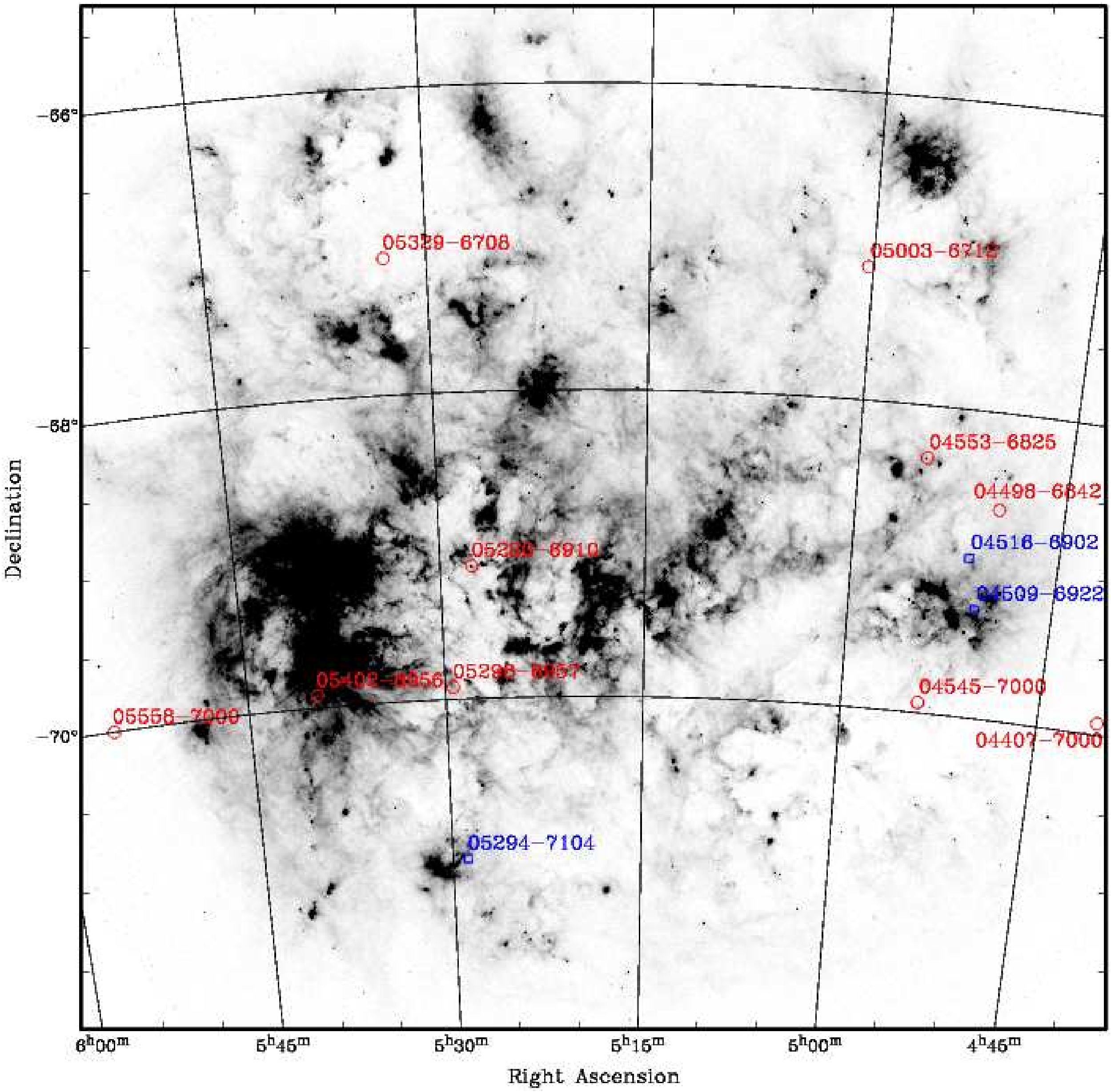

Fig. 2.— Detected circumstellar OH masers (red circles) and candidate OH/IR stars (blue squares) in the Large Magellanic Cloud, on a 24-μm *Spitzer* image (Meixner et al. 2006).

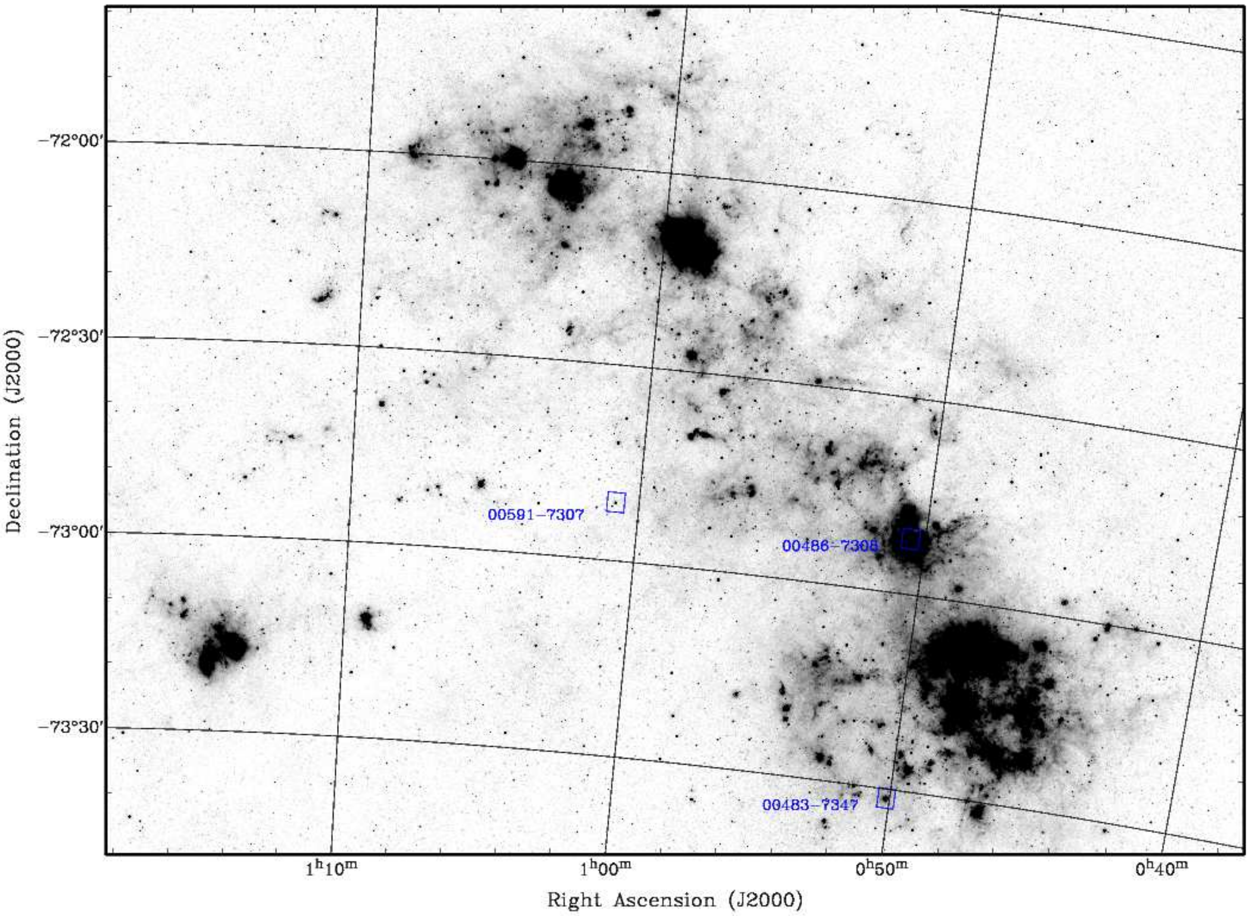

Fig. 3.— Candidate OH/IR stars in the Small Magellanic Cloud, on a 24-μm *Spitzer* image (Gordon et al. 2011).

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