Astron. Astrophys. 287, 479–492 (1994)

ASTRONOMY AND ASTROPHYSICS

A deep VLA search for OH (1612 MHz) maser sources in the galactic plane

J.A.D.L. Blommaert*, **H.J. Van Langevelde****, **and W.F.P. Michiels**

Leiden Observatory, P.O. box 9513, NL-2300 RA Leiden, The Netherlands

Received 25 November 1993 / Accepted 21 February 1994

Abstract. The results of a VLA OH (1612 MHz) search for OH/IR stars in 7 fields along the galactic plane are presented. Forty-four sources were detected of which 35 were not previously known. It is shown that "blind" radio interferometric observations (such as with the VLA) are capable of filling up the gap in the IRAS based OH surveys near the galactic plane. This is important for the dynamical modelling of the disc and bulge of our Galaxy. It is also demonstrated that the high resolution of a synthesis telescope is needed to avoid confusion in the galactic plane. Most detected sources are likely to be young ($\lesssim$ 1 Gyr) and massive ($M_{\rm ms} > 2 - 3 M_\odot$) evolved stars and have high expansion velocities ($v_{\rm exp} > 14.5$ km/s) and small deviations (< 10 km/s) from galactic rotation. Like Baud et al. (1981) we find a peak in the number of sources around $l = 25°$, a region associated with active star formation and a low number of stars at $l = 5°$ and $10°$.

Key words: stars: AGB, post-AGB – techniques: interferometric – masers – surveys – radio lines: stars

1. Introduction

The strong OH masers at 1612 MHz originate predominantly in circumstellar shells formed around evolved stars. In most cases this can be readily recognized by the two–peak signature of the 1612 MHz profile. The separation of these peaks equals twice the outflow velocity $v_{\rm exp}$ of the circumstellar OH, typically 10 to 25 km/s. The circumstellar shell is created by a high stellar mass loss (up to $10^{-5} - 10^{-4} M_\odot/yr$). The dust in the shell absorbs the stellar radiation and reemits it in the far infrared. This infrared radiation is thought to be responsible for the pumping of the maser emission originating in the outflowing OH shell (see Herman & Habing 1985 and Cohen 1989 for reviews on OH/IR stars).

OH/IR stars have been found to be useful tracers of the structure of the Galaxy, especially in regions in the inner Galaxy where optical studies are hampered by high extinction. Due to the bright OH maser emission and the high far infrared luminosity (several thousand $L_\odot$) they can be detected throughout a large part of the Galaxy. From the OH line profile the stellar velocity can be derived, which enables one to study the kinematics of the OH/IR stars. Several OH surveys have been performed, using single dish telescopes, especially in a strip along the galactic plane (e.g. Baud et al. 1979; Caswell & Haynes 1975; Johansson et al. 1977). A compilation of data before 1983 on 442 OH sources can be found in te Lintel Hekkert et al. (1989). These early surveys along the galactic plane showed a distribution of OH/IR stars that peaks at 4.5 kpc from the galactic centre (Baud et al. 1981). This is similar to what was found for HII regions and CO clouds (see for instance Burton & Gordon 1978; Dame et al. 1987; Burton 1988), which led Baud et al. (1981) to the conclusion that at least part of the OH/IR stars are relatively young objects. It has also been demonstrated that the OH/IR stars are not a kinematically homogeneous sample, but that they can be divided in groups on basis of the expansion velocities of the shells (Baud et al. 1981 and te Lintel Hekkert 1990). The high expansion velocity sources are believed to be younger as is strongly suggested by the longitude/stellar velocity distribution (as detailed beyond in this paper). The higher expansion velocity for the younger objects may be explained by the fact that the expansion velocity is greatly dependent on radiation pressure on the dust in the circumstellar shell and is therefore connected to the stellar luminosity (Jura 1986). There is also a dependence on the dust-to-gas ratio in the shell (Blommaert et al. 1993 and Habing et al. 1994).

A major improvement in the study of OH/IR stars was made by the discovery of several thousands of candidate OH/IR stars by the infrared IRAS satellite (IRAS Point Source Catalogue 1985). The nature of the IRAS sources was confirmed by surveys that were performed at 18 cm (e.g. Eder et al. 1988; Sivagnanam et al. 1988; Gaylard et al. 1989; Likkel 1989; Lewis et al. 1990; te Lintel Hekkert et al. 1991a; David et al. 1993). The IRAS

Send offprint requests to: J. Blommaert (IAP)

* Present address: CNRS, Institut d'Astrophysique de Paris, 98bis, Blvd Arago, F-75014 Paris, France

** Present address: JIVE, Radiosterrenwacht Dwingeloo, Postbus 2, NL-7990 AA Dwingeloo, The Netherlands

Table 1. Log of the observing runs

Field $b = 0°$	Pointing centre (1950)		Observing time [UT]			map noise [mJy/beam]
$l = 5°$	$17^h53^m60^s.00$	-24°37′59″.00	02 FEB 91	15:00	15:57	9.6
$l = 10°$	18 04 47.00	-20 17 51.00	08 NOV 90	20:50	23:17	7.0
$l = 15°$	18 14 59.00	-15 55 24.00	08 NOV 90	23:26	01:53	7.4
$l = 17.5°$	18 19 54.47	-13 43 29.21	02 FEB 91	16:06	18:21	7.6
$l = 22.5°$	18 29 29.97	-09 18 39.23	02 FEB 91	18:29	20:44	7.0
$l = 25°$	18 34 12.00	-07 05 51.00	08 NOV 90	18:27	20:41	9.9
$l = 30°$	18 43 28.42	-02 39 47.47	02 FEB 91	12:57	14:51	12.0

based samples have been used to derive the structure of the galactic disc (Habing 1988). Te Lintel Hekkert's sample has been used for a dynamical analysis (te Lintel Hekkert et al. 1991b). However, these studies are hampered by the fact that the IRAS survey was confusion limited along the galactic plane. Therefore the IRAS based surveys are restricted to $|b| > 3°$. This restriction poses problems for the analysis, because we miss the bulk of the disc population in the IRAS based surveys.

More extensive studies along the galactic plane are necessary. Basic problems for single dish surveys are the presence of strong continuum sources and a high OH/IR star number density. The problems can be overcome by using an aperture synthesis radio instrument such as the VLA. An example of such a survey is the work by Lindqvist et al. (1992a) for the galactic centre. A survey of continuum sources along the galactic plane with the VLA by Becker et al. (1992) resulted in a serendipitous discovery of OH/IR stars. This survey did not give any information on the velocity of the OH/IR stars, due to the nature of their search. In our paper the results of a deep search with the VLA in 7 fields along the galactic plane will be presented. A comparison with the distributions based on the IRAS surveys at higher latitudes will be made and the connection with star-forming regions in the Galaxy will be studied. In the next section, the technical aspects of the observations, the data reduction and the search technique will be discussed. This is followed by Sect. 3 where we list all the detected sources. In Sect. 4 the distributions of the sample in longitude and velocity will be described.

2. Observations, data handling and search technique

Observations at 18 cm were carried out with the VLA[1] on November 8/9, 1990 and February 2, 1991, both in CD configuration. The observing bandwidth was set to 3.125 MHz, equivalent to 581 km/s, which was divided into 256 channels, each 2.27 km/s wide. The spectra were determined with uniform weighting in order to keep the full spectral resolution as well as the large total bandwidth. Such a setup of the VLA correlator allows the recording of only a single circular polarisation, which was RR. In total seven pointing positions along the galactic plane were observed, each with slightly different integration times (see Table 1). For all fields the centre of the band was set at $v_{\rm lsr}$ = 50 km/s. This results in a final good quality coverage from approximately $v_{\rm lsr} = -220$ to 320 km/s. The synthesized beams were typically 43″ × 36″ (HPBW).

The data were calibrated with the AIPS package. Flux and bandpass calibration was done against 1328+307. The sources 1328+307, 1819–096 and 1748–253 were used to do phase calibration. Several scans containing bad data (i.e. abrupt amplitude variations in time) were flagged. Especially a considerable fraction of the data on the field of $l = 30°$ was lost.

To automate the search for OH/IR stars in these data sets, the quite considerable continuum contribution needs to be subtracted first. This was done using a visibility based method (Van Langevelde & Cotton 1990; Cornwell et al. 1992) where the outermost channels of good quality are used to estimate the continuum emission over the whole bandwidth.

After the continuum subtraction, data cubes of size 512 × 512 × 256 with pixel size 6″, were constructed that cover the entire primary beam (HPBW ≈ 27.5′). The maps were calculated with natural weighting of the visibilities; this results in the best sensitivity for point sources. The resulting images were cleaned because the bright OH masers can sometimes dominate a spectral plane. The resulting cubes were searched systematically for OH/IR stars in the following way. At each position the spectrum was searched for emission in excess of the noise. All points with a flux density $F_\nu > 6\,\sigma$ are obvious candidates for OH/IR stars. In the whole database discussed here one can expect only 0.003 of such 6 σ points to occur as noise fluctuations, assuming a normal noise distribution. Also spectra containing a peak of $F_\nu > 4\sigma$ which is accompanied by a second peak with $F_\nu > 3.8\sigma$ are possible detections if they are separated by more than 6 km/s. The expectation value for this is 0.7 spontaneous double peaks in the whole database. All the automatically found candidate OH/IR star spectra were inspected by eye. In this process we were especially cautious not to take sidelobes of bright sources as separate sources.

[1] The Very Large Array (VLA) is operated by the National Radio Astronomy Observatory under cooperative agreement with the National Science Foundation.

3. Data set

After visual inspection of the sources found with the automatic search program a list of 44 sources remained of which 35 were previously unknown. The properties of the resulting sources are listed in Table 2. Spectra were constructed by making small cubes for which the continuum was subtracted by using the clear spectral channels directly bracketing the OH/IR star signature. The data were corrected for primary beam attenuation, using the standard AIPS procedure. Positions were obtained by fitting a gaussian profile to the brightest image plane. Typical positional accuracy is $\approx 4''$. The ratio of integrated over peak flux density in the gaussian fit is used to correct the peak flux in every frequency channel. The resulting spectra are shown in Fig. 1.

The $v_{\rm blue}$ and $v_{\rm red}$ are measured at the channels of the outermost maxima in the spectra. Thirty-six objects have the traditional double peaked spectrum for OH/IR stars, 8 have only single peaks. Their fluxes were all close to the detection limit and they may have a second peak which is too weak to be detected. In fact, we have detected a second peak for 2 sources which were previously reported to have only a single peak: OH 24.762−0.085 and OH 25.154+0.061 (see next subsection).

Two sources outside the searched area were strong enough to be detected through their sidelobes: OH 24.731−0.087 ($v_{\rm blue}$ = 34.1 km/s and $v_{\rm red}$ = 68.2 km/s) and OH 30.450−0.018 ($v_{\rm blue}$ = 79.6 km/s and $v_{\rm red}$ = 120.5 km/s). No reliable flux determinations for these sources can be made and they were discarded in the subsequent analysis.

3.1. Individual sources in the literature

In Table 3 we have listed the 9 sources which were already known from previous OH surveys. The following OH (1612 MHz) catalogues were searched: te Lintel Hekkert et al. (1989) (LVHW from now on), which gives a compilation of data on pre-IRAS detected OH-sources, all 9 sources were in this list; Becker et al. (1992) and Benson et al. (1990) were also searched. Many positions in LVHW come from single dish OH observations which can have positional errors up to 10′. Becker et al. (1992) discovered 50 OH sources in a search with the VLA for continuum sources along the galactic plane. With their technique no velocity information can be obtained. Three of our sources were found in this list and match the positions to within a few arcseconds. The Benson et al. (1990) catalogue is like LVHW a compilation of data on maser sources but includes other lines and contains also more recent data; all 9 sources were found in this catalogue too. In the te Lintel Hekkert et al. (1991a) survey based on IRAS sources no match with our detections has been found. This does not come as a surprise as this survey was incomplete for $|b| < 3°$. For most sources identified in any of the surveys the velocity and position are in agreement within the errors. The position determination in our survey is much more accurate because of the use of an interferometer. Some differences are found between the measured OH fluxes and those stated in the literature, but in general not more than a factor of two. This is in agreement with the expected variation for OH/IR stars (Herman & Habing 1985). We now give comments on some individual sources.

<u>OH 10.077−0.095</u> is classified as a supergiant by Jones et al. (1988). The object is associated with IRAS 18052–2016. This IRAS source has very red IRAS colours (F_{60} / F_{25} = 2.5) and a low variability index (07). Furthermore the star has a high expansion velocity ($v_{\rm exp}$ = 27 km/s).

<u>OH 17.146−0.200:</u> Our position differs by about 4′ from the one stated in Baud et al. (1979) which is based on a single dish telescope observation; their velocity measurement of the single peak matches our measurement. The new position is closer to IRAS 18198–1408, which has been associated with the OH source by LVHW. This IRAS source has only a reliable 25 μm measurement, has a low IRAS variability index (04) and is associated with a nebula LDN 0380, so that it is not clear whether the IRAS identification is physically associated with the OH maser. Like Baud et al. we were not able to detect a second peak; this may be due to the fact that the source is situated near the edge of the field where the sensitivity is low.

<u>OH 17.392−0.289:</u> The position differs by 9″ from the one stated in LVHW. It is associated by LVHW with IRAS 18211–1357. Our more accurate position shows that the association with the IRAS source is unlikely (see also next subsection). The OH variability has been monitored by Van Langevelde et al. (1990); a period of 1667 (±144) days was found.

<u>OH 17.551−0.126:</u> This source is associated with IRC −10414 and AFGL2139. There seems to be some confusion around this position; LVHW gives stellar and expansion velocities that are inconsistent with the peak velocities. In the literature we found references to 2 sources at this position. One is classified as a type I OH/IR star and has been reported by Engels (1979) to have 1665/1667 MHz maser emission at 28 and 47 km/s, which could be compatible with the observed velocities of the 1612 MHz maser (27 and 59 km/s), as it is often found that the main lines occur at lower velocities (Cohen 1989). H_2O and SiO maser emission with $v_{\rm lsr} \approx 42$ km/s (Engels 1979; Lada et al. 1981; Ukita & Goldsmith 1984) has also been found and is in agreement with our stellar velocity ($(v_{\rm blue}+v_{\rm red})/2$ = 43.2 km/s). The other source has $v_{\rm lsr} \approx 20$ km/s (Barcia et al. 1985 and Jewell et al. 1985). It has only been reported as an SiO maser source but the 20 km/s was assumed by Jewell et al. (1985) to be the central velocity of the OH masering source. We conclude that OH 17.551−0.126 has a stellar velocity similar to the former H_2O and SiO maser (with $v_{\rm lsr} \approx 42$ km/s).

<u>OH 22.772−0.256:</u> The position differs by approximately 3′ from the position in LVHW. Our position is closer to IRAS 18308–0911 with which it is identified (LVHW). The source is also associated with CRL 2188. Benson et al. (1990) indicate a spectral classification of M6.5, but this may be a misidentification. Allen et al. (1977) mention a second source which is closer to the CRL 2188 position and which is invisible and has redder near-infrared colours. They claim that this is probably the CRL 2188 source; it is also closer to our OH

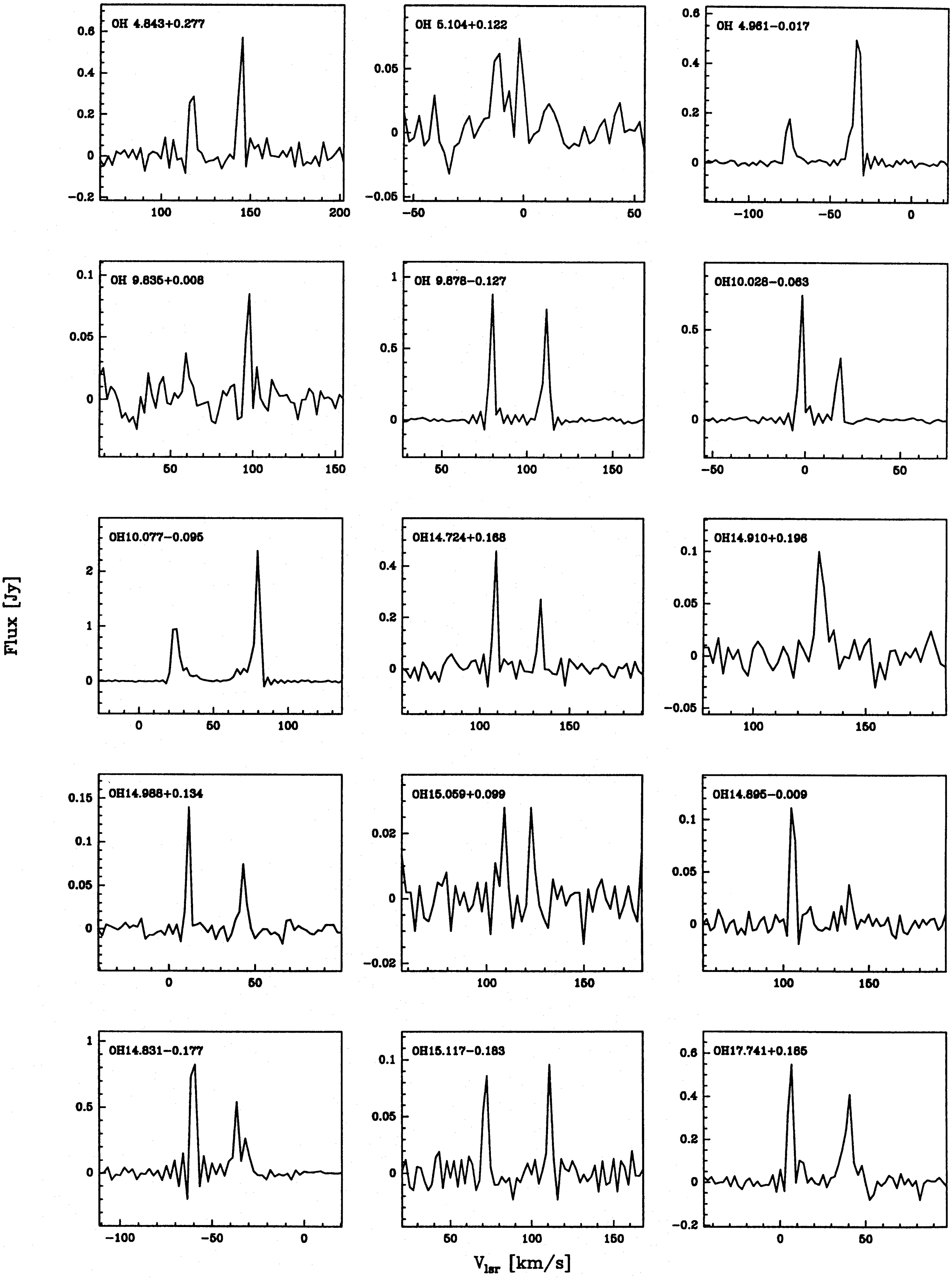

Fig. 1. The 1612 (MHz) spectra of the OH sources

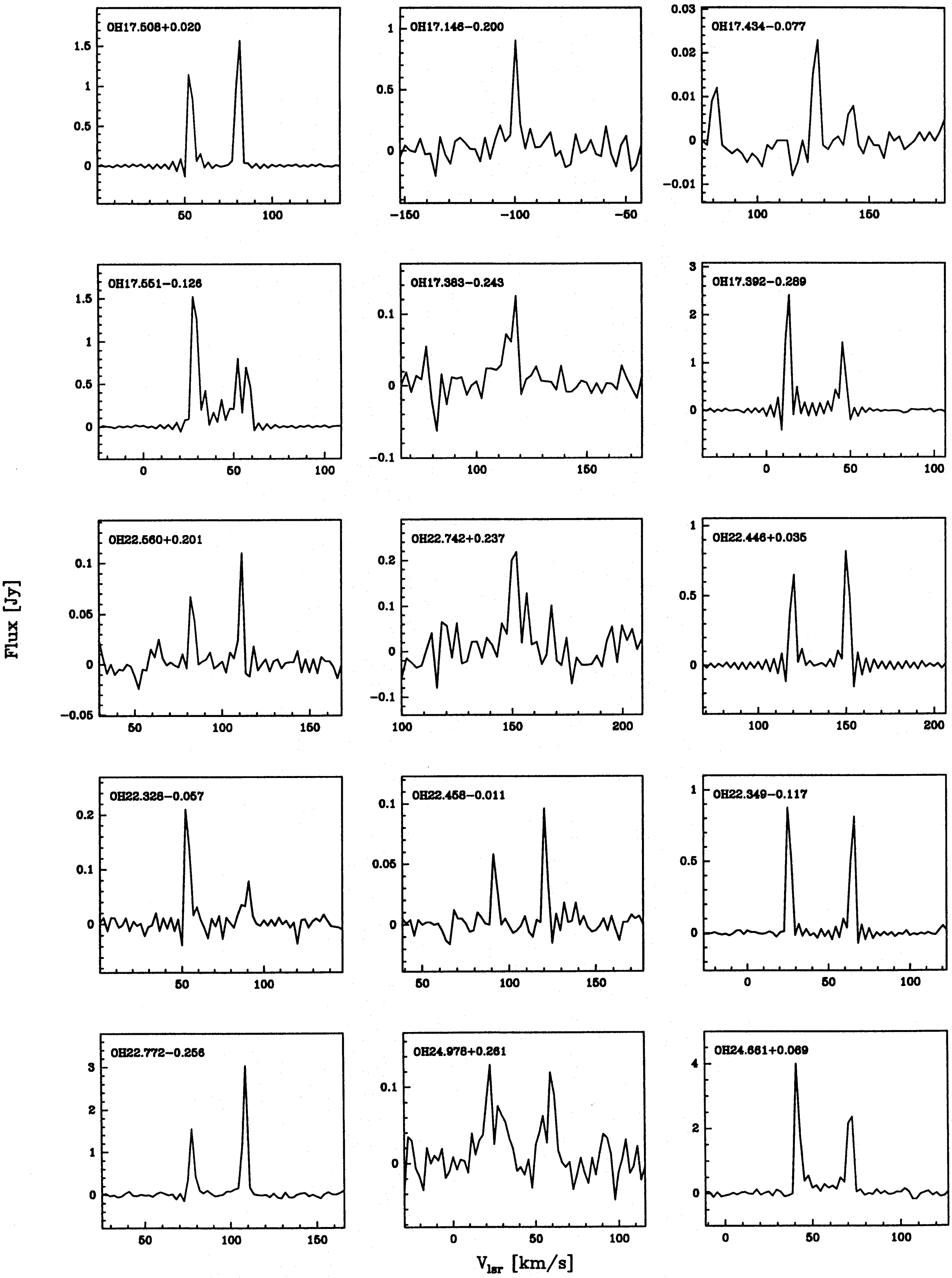

Fig. 1. (continued)

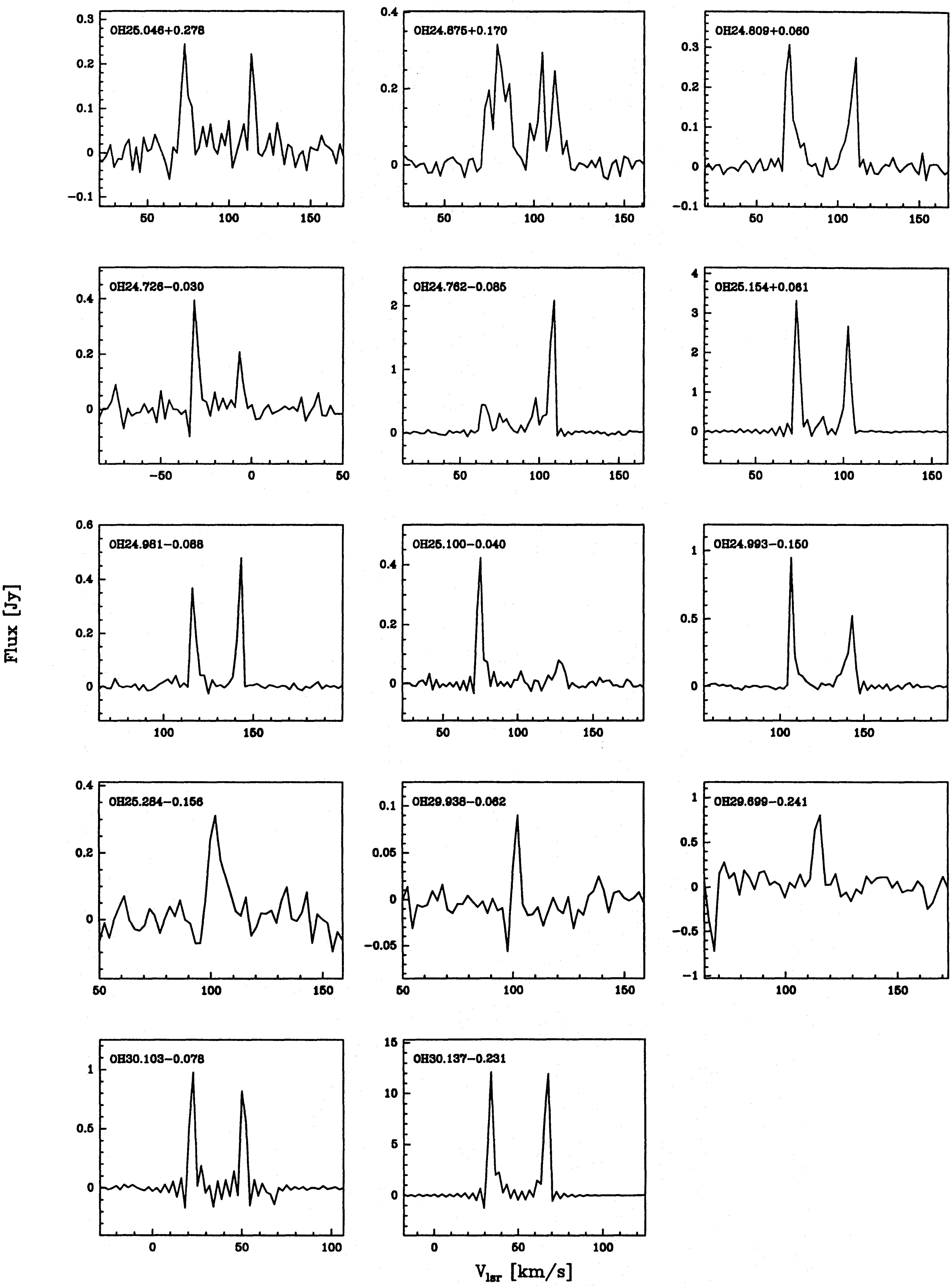

Fig. 1. (continued)

Table 2. Detected sources with their positions, the velocities and the peak fluxes. The last column contains the primary beam correction

Name	Position (1950)		$v_{\rm blue}$ [km/s]	$v_{\rm red}$	$F_{\rm blue}$ [Jy]	$F_{\rm red}$	PBC
OH 4.843+0.277	$17^h52^m35\overset{s}{.}97$	$-24°37'43\overset{''}{.}6$	118.1	145.3	0.288	0.573	4.05
OH 5.104+0.122	17 53 46.11	−24 28 36.0	-11.3	-2.2	0.062	0.074	1.42
OH 4.961−0.017	17 53 58.82	−24 40 31.5	-74.9	-34.0	0.177	0.497	1.01
OH 9.835+0.008	18 04 24.57	−20 26 17.7	59.1	97.7	0.037	0.085	1.43
OH 9.878−0.127	18 05 00.36	−20 28 02.7	79.5	111.3	0.880	0.776	1.51
OH 10.028−0.063	18 05 04.77	−20 18 16.6	-2.2	18.2	0.694	0.344	1.04
OH 10.077−0.095	18 05 17.95	−20 16 41.0	25.0	79.5	0.948	2.372	1.19
OH 14.724+0.168	18 13 48.70	−16 05 15.3	109.0	134.0	0.458	0.270	4.43
OH 14.910+0.196	18 14 05.21	−15 54 31.5	129.4		0.100		1.86
OH 14.988+0.134	18 14 28.11	−15 52 12.2	11.4	43.1	0.140	0.075	1.25
OH 15.059+0.099	18 14 43.65	−15 49 38.1	109.0	122.6	0.028	0.028	1.16
OH 14.895−0.009	18 14 48.44	−16 01 16.0	104.5	138.5	0.111	0.038	1.13
OH 14.831−0.177	18 15 17.54	−16 09 26.3	-59.0	-36.3	0.827	0.543	2.22
OH 15.117−0.183	18 15 52.69	−15 54 39.3	72.7	111.3	0.086	0.096	1.85
OH 17.741+0.185	18 19 42.41	−13 25 29.2	6.9	40.9	0.549	0.410	3.49
OH 17.508+0.020	18 19 51.17	−13 42 31.0	52.3	81.8	1.141	1.570	1.00
OH 17.146−0.200	18 19 57.03	−14 08 09.7	-99.8		0.906		16.06
OH 17.434−0.077	18 20 03.04	−13 49 19.2	127.2		0.023		1.12
OH 17.551−0.126	18 20 27.82	−13 44 24.1	27.3	59.1	1.522	0.701	1.25
OH 17.383−0.243	18 20 33.46	−13 56 46.0	118.1		0.125		2.66
OH 17.392−0.289	18 20 44.64	−13 57 29.1	13.7	45.5	2.409	1.429	3.68
OH 22.560+0.201	18 28 53.81	−09 09 48.9	81.8	111.3	0.067	0.110	1.79
OH 22.742+0.237	18 29 05.04	−08 59 04.1	152.1		0.218		5.41
OH 22.446+0.035	18 29 16.01	−09 20 35.7	120.4	149.9	0.649	0.819	1.04
OH 22.328−0.057	18 29 22.56	−09 29 23.6	52.3	90.9	0.210	0.078	1.54
OH 22.458−0.011	18 29 27.99	−09 21 09.4	90.9	120.4	0.058	0.096	1.01
OH 22.349−0.117	18 29 37.88	−09 29 59.3	25.0	65.9	0.875	0.810	1.62
OH 22.772−0.256	18 30 55.85	−09 11 27.8	77.2	109.0	1.545	3.029	8.45
OH 24.978+0.261	18 33 12.50	−06 59 18.1	22.8	59.1	0.129	0.119	2.61
OH 24.661+0.089	18 33 15.08	−07 21 26.9	40.9	72.7	4.001	2.362	6.07
OH 25.046+0.278	18 33 17.28	−06 55 45.0	72.7	113.6	0.245	0.222	2.88
OH 24.875+0.170	18 33 21.72	−07 07 49.9	75.0	111.3	0.196	0.247	1.80
OH 24.809+0.060	18 33 37.71	−07 14 24.6	70.4	111.3	0.308	0.275	1.71
OH 24.726−0.030	18 33 47.90	−07 21 21.2	-31.7	-6.7	0.394	0.207	2.76
OH 24.762−0.085	18 34 03.59	−07 20 51.5	63.6	109.0	0.444	2.084	2.32
OH 25.154+0.061	18 34 16.15	−06 55 59.2	72.7	102.2	3.322	2.679	1.42
OH 24.981−0.088	18 34 28.63	−07 09 19.5	115.9	143.1	0.367	0.479	1.09
OH 25.100−0.040	18 34 31.37	−07 01 37.9	75.0	127.2	0.423	0.079	1.13
OH 24.993−0.150	18 34 43.25	−07 10 23.1	106.7	143.0	0.949	0.523	1.33
OH 25.284−0.156	18 35 16.51	−06 55 08.3	102.2		0.312		4.17
OH 29.938−0.062	18 43 35.40	−02 44 36.1	102.2		0.090		1.08
OH 29.699−0.241	18 43 47.61	−03 02 43.8	115.9		0.804		11.25
OH 30.103−0.078	18 43 56.62	−02 36 29.2	22.8	50.0	0.977	0.820	1.22
OH 30.137−0.231	18 44 33.07	−02 38 55.0	34.1	68.1	12.095	11.911	2.61

position. Engels (1979) classified the object as a type II OH/IR star.

OH 24.762−0.085: This source was so far only known as a single peak maser (LVHW). Next to the peak at 106 km/s we find a second one at 66 km/s. Our position differs by 1′ from the previous value. According to Baud et al. (1985) it is situated at a kinematical distance of 9.1 kpc and has a bolometric luminosity of $6.5 \times 10^4 L_\odot$.

OH 25.154+0.061: Also for this source only one peak was previously known at 73.2 km/s (LVHW). A second peak is now detected at 102 km/s. The positions are fully consistent.

Table 3. Sources for which an IRAS counterpart was found. The IRAS PSC 12, 25 and 60 μm fluxes and the variability index (VAR) are given. The bracketed values have IPSC quality 1. The latter column indicates the sources which were found in the literature; 1: was found in LVHW and Benson et al. (1990), 2: was also found in Becker et al. (1992).

OH Name	IRAS Name	F_{12}	F_{25} [Jy]	F_{60}	VAR	Lit.
OH 4.843+0.277	17526−2437	2.1	3.2	(352.0)	58	
OH 4.961−0.017	17539−2440	3.2	4.6	(15.8)	97	
OH 9.835+0.008	18044−2026	5.2	5.1	(16.6)	11	
OH 9.878−0.127	18050−2028	4.9	8.4	(20.9)	89	1
OH 10.077−0.095	18052−2016	21.4	32.5	82.4	7	1,2
OH 14.724+0.168	18137−1605	2.0	7.6	(25.8)	60	
OH 14.910+0.196	18140−1554	2.2	(6.6)	(24.2)	-	
OH 14.988+0.134	18139−1552	5.7	5.1	(23.3)	84	
OH 15.059+0.099	18143−1549	2.2	2.2	(20.7)	37	
OH 14.895−0.009	18148−1601	(1.7)	2.38	(19.3)	11	
OH 14.831−0.177	18152−1609	(4.4)	1.8	(19.8)	-	
OH 15.117−0.183	18159−1554	6.3	4.3	(38.6)	15	
OH 17.741+0.185	18197−1325	(8.5)	7.5	(22.5)	99	
OH 17.508+0.020	18198−1342	11.6	10.9	(21.0)	99	
OH 17.146−0.200	18198−1408	(8.1)	4.7	(248.0)	4	1
OH 17.434−0.077	18200−1348	(4.0)	(3.6)	57.7	-	
OH 17.551−0.126	18204−1344	495.9	325.6	73.1	39	1,2
OH 17.392−0.289						1,2
OH 22.328−0.057	18293−0929	4.4	5.0	(42.4)	11	
OH 22.349−0.117	18296−0929	12.8	(13.3)	(86.3)	97	
OH 22.772−0.256	18308−0911	17.7	80.8	(1075)	0	1
OH 25.046+0.278	18332−0655	4.5	5.0	(17.9)	78	
OH 24.875+0.170	18333−0707	2.5	6.8	(91.0)	52	
OH 24.762−0.085	18340−0720	30.8	(41.9)	142.7	99	1
OH 25.154+0.061	18342−0655	8.1	31.7	423.9	61	1
OH 24.981−0.088	18345−0709	6.5	12.6	(93.2)	0	
OH 25.100−0.040	18345−0701	23.2	21.71	19.6	56	
OH 24.993−0.150	18348−0711	4.8	(6.4)	(16.4)	-	
OH 25.284−0.156	18352−0655	42.6	72.8	(41.9)	48	
OH 29.699−0.241	18437−0302	4.8	8.6	(18.2)	17	
OH 30.103−0.078	18439−0236	(2.9)	4.5	(25.0)	1	
OH 30.137−0.231						1

OH 30.137−0.231: For the brightest object in our sample we find exactly the same position as stated in the literature. As the uncertainty of the position is now very small we can exclude the IRAS counterpart 18445–0238 given by LVHW. The OH variability has been monitored by Van Langevelde et al. (1990). They find a period of 2013 (±243) days.

In the literature, some confusion exists around OH 17.6+0.2. In a search for OH maser emission by Allen et al. (1977) at the position of CRL2136 a relatively weak source was found with peaks of 0.3 Jy at 22 and 40 km/s and possibly a peak at 6 km/s. According to Cohen et al. (1988) an OH/IR star with peaks at 6 and 24 km/s is more likely. They also mention the possibility of confusion and suggest interferometric observations to solve this. We find peaks at 6.9 and 40.9 km/s for OH 17.741+0.185. The position differs by 5.5′ from the CRL2136 coordinates. The confusion around this position stresses again the importance of interferometric measurements in high source density regions like the galactic plane.

3.2. IRAS identifications

IRAS counterparts of the OH maser sources have been searched for on the basis of positional coincidence. Thirty sources were found for which the OH position was well within the uncertainty of the IRAS position given in the PSC (up to $\approx 1'$). All associations are listed in Table 3. Most of these IRAS positions are within a few arcseconds from the VLA position. Many objects have only upper limits on the fluxes in one or more bands (IPSC quality 1) which are unreliable in high density regions like the galactic plane which also has a high far infrared background flux. The high source density may also lead to some confusion. However, there are some arguments that strengthen the identifications made. First, the IRAS [12]−[25] colour (= $-2.5\log(F_{12}/F_{25})$) for the sources with good quality fluxes are in the range expected for OH/IR stars. Te Lintel Hekkert (1990) and other authors demonstrated that most OH masering IRAS sources have colours in the range $-1 \lesssim [12] - [25] \lesssim 1$, although [12]−[25] colours up to 2.5 also occur. This range is in agreement with the one in our sample: $-0.46 < [12] - [25] < 1.65$ for the sources with well determined IRAS 12 and 25 μm fluxes (IPSC quality 2 or 3). Several authors (e.g. Eder et al. 1988; Likkel 1989; Sivagnanam & Le Squeren 1989; te Lintel Hekkert 1990; Becker et al. 1992) have observed a tendency towards somewhat redder colours for sources closer to the galactic plane. Moreover, half the sources have an IPSC variability index above 50 (VAR gives the probability that a source is variable), which is expected if the source is a variable OH/IR star.

Of the 9 IRAS counterparts given by LVHW we find that 2 are misidentified. This is better than expected taking into consideration that their identification was based on less accurate OH positions and the high number density of IRAS sources in this region.

Fourteen sources do not have an IRAS counterpart. In some cases this may be due to a strong adjacent source (i.e. an HII region). However, there is a tendency that more weaker OH sources have been missed by IRAS; for the brightest 22 sources 5 do not have IRAS counterpart and in the weaker half of the sample there are 9 objects without an IRAS counterpart. Distance may play a role as can be shown as follows. Van der Veen & Breukers (1989) have derived a bolometric correction on the 12 μm flux density which is almost constant for this type of stars ($BC_{12} = 2.8 \pm 0.2$). The luminosity then equals

$$L_* = 1390 \cdot (F_{12}/\mathrm{Jy}) \cdot (D/8\,\mathrm{kpc})^2 L_\odot. \quad (1)$$

The weakest 12 μm fluxes in Table 3 are in the range of 2 to 3 Jy. According to Habing (1988) and te Lintel Hekkert (1990) the peak of the luminosity distribution of the OH/IR stars in the disc is at 4000 to 5000 $L_\odot$. At a distance of 8 kpc these stars have F_{12} values of around 3 Jy. If the weak OH fluxes are predominantly at larger distances than 8 kpc they may have been missed by IRAS.

3.3. Completeness limits

The data cubes that were inspected for OH/IR stars have a field size of 51.2 arcminutes square. This covers a very large part of the primary beam. In fact the full area enclosed in the factor 20 attenuation radius is covered. This implies that the survey is formally only complete for very bright objects. Only sources with peak flux densities above 12 Jy could have been detected over 99% of the field.

In Fig. 2 we show the distribution of the flux densities of the brightest OH feature of each source in the sample. The peak flux is a useful quantity if we want to discuss the detection statistics of the sources; it determines whether a source is found.

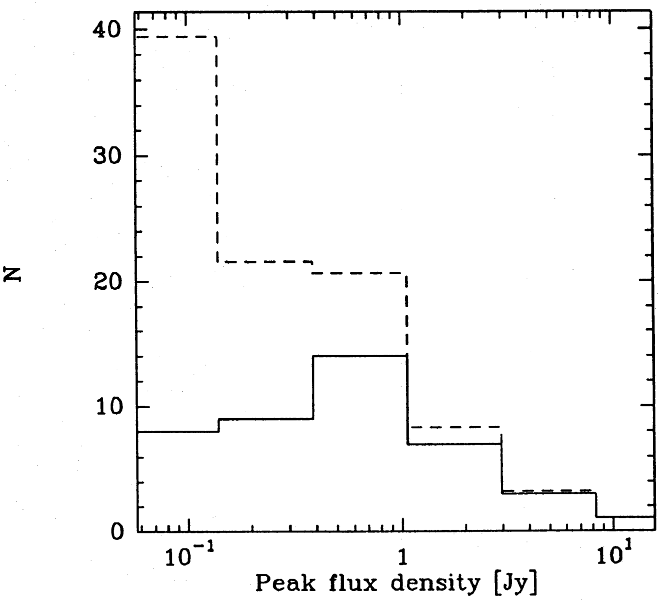

Fig. 2. The distribution of the peak flux densities, the dashed line indicates the distribution after correction for completeness

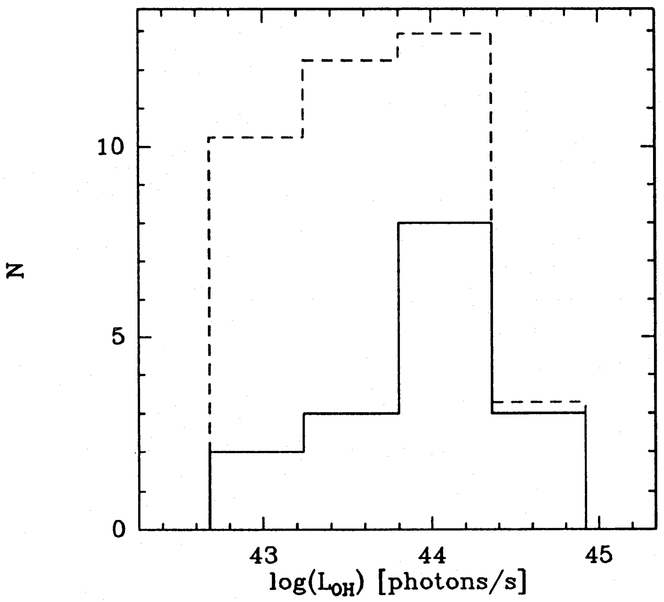

Fig. 3. The distribution of 1612 MHz luminosity for a subsample of OH sources for which a statistically reliable distance estimate could be obtained

In our sample peak flux densities range from 12 Jy down to 23 mJy. The dashed line indicates the distribution of peak flux densities corrected for incompleteness. The correction is made by weighting every source by the inverse fraction of the survey area in which the source could have been detected. We have based this correction only on the criterion that one of the peak flux densities exceeds the 6σ detection threshold. In this procedure we have taken into account the differences in sensitivity for each field of the survey. Because the survey is formally incomplete

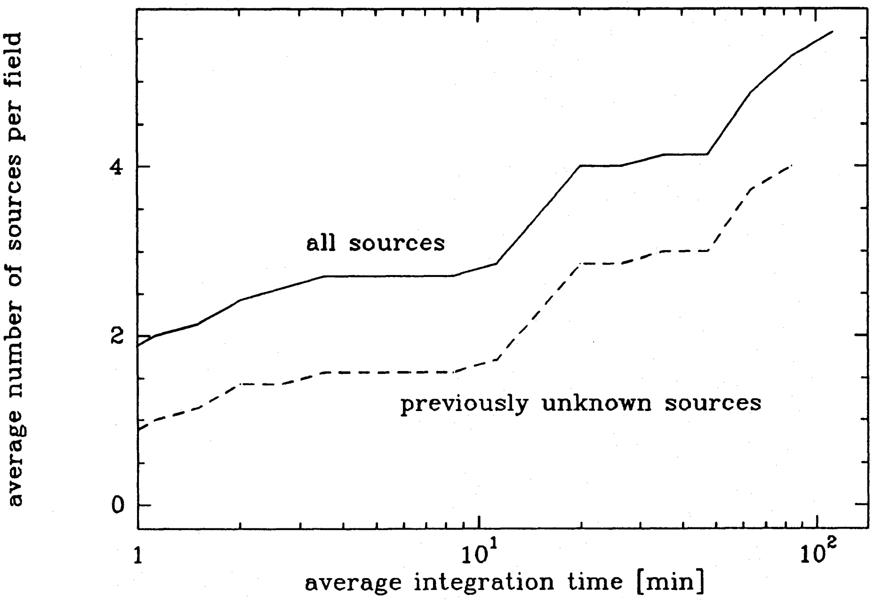

Fig. 4. The average number of sources detectable per field as a function of observing time

for almost every flux level, the correction is never exactly 1. We should bear in mind that the distribution is slightly broadened by the variability typical of OH/IR stars. We have not attempted to correct for this; a statistical correction would be very uncertain and this is an effect present in all OH/IR star surveys. Another complication in the comparison with other surveys is that the measured peak flux densities depend on the frequency resolution of different surveys, because the profiles are unresolved (Baud et al. 1981).

The integrated flux in the 1612 MHz line is independent of frequency resolution. If the distances to these sources were known we could estimate the OH luminosity. From the (l, v) distribution (next section) it is clear that a large fraction of the sources does follow galactic rotation. Therefore we may try to use kinematical distances. For every field we use the distance corresponding to the tangential velocity as a rough guess for the typical distance for the sources that have velocities close to this maximum value. This has been done for a sub-selection from the sample of sources for which both distances which correspond to the same radial velocity do not differ by more than 30% from the distance adopted for the tangential velocity in that field (Burton 1988). In Fig. 3 the results are shown, with the same correction for incompleteness in the survey applied. Due to the limited number of sources and the large uncertainties a quantitative result is not attempted. However, we can say that the brightest sources in our sample have OH luminosities of $\sim 10^{44}$ photons/s, comparable to the brightest sources in other samples, that have independent distance measurements (Herman & Habing 1985; Lindqvist et al.1989). A comparison of the OH luminosity distribution of our sample with that of the Herman & Habing (1985) sample is difficult, as their work contains sources at a large range of distances and the selection effects are unclear. This is different for the sample of the galactic centre stars of Lindqvist et al. where all sources are at approximately the same distance. The relative contribution of bright sources is certainly higher in our sample in comparison with the galactic centre sample. Their distribution shows a strong increase in numbers from $L_{OH} = 10^{42.8}$ (photons/s) and then decreases gradually beyond $10^{43.1}$; only a small fraction of stars have $L_{OH} > 10^{43.8}$ (photons/s) in contrast to our sample where the number of sources is still high for such high OH luminosities. As expected from models, Sivagnanam et al. (1989) demonstrated a correlation between the far infrared flux ($\approx 25\mu m$) and the OH 1612 MHz luminosity, so that we conclude that our sources are predominately bright, very red sources.

Figure 2 shows that more sources can be detected in even deeper surveys. For $N \sim F^{\alpha}_{\rm peak}$, we find $\alpha \approx -0.7$. This relatively shallow increase implies that with a given amount of telescope time one can find vastly more OH/IR sources by surveying a large area than by getting to a low noise level. This is illustrated in Fig. 4 which displays the average number of detections per field we would have had if the total integration time had been shorter. Here we have assumed that the noise scales as the square root of the observing time. Also shown is how many previously unknown sources would have been detected. The two lines in this figure run almost parallel, because previously known sources are so bright they can be detected easily by the VLA within one minute.

4. Longitude and velocity distribution

4.1. Expansion velocity

Before describing the distributions of the sample of OH sources as function of longitude and radial velocity, we discuss an important parameter, namely the expansion velocity $v_{\rm exp}$ of the circumstellar shell, defined as $|v_{\rm blue} - v_{\rm red}|/2$. Several authors have used $v_{\rm exp}$ to distinguish between "old" and "young" stars (Baud et al. 1981; te Lintel Hekkert 1990). Although the mass loss mechanism is not quite clear, it is believed that two parameters define the final outflow velocity at large distances of the

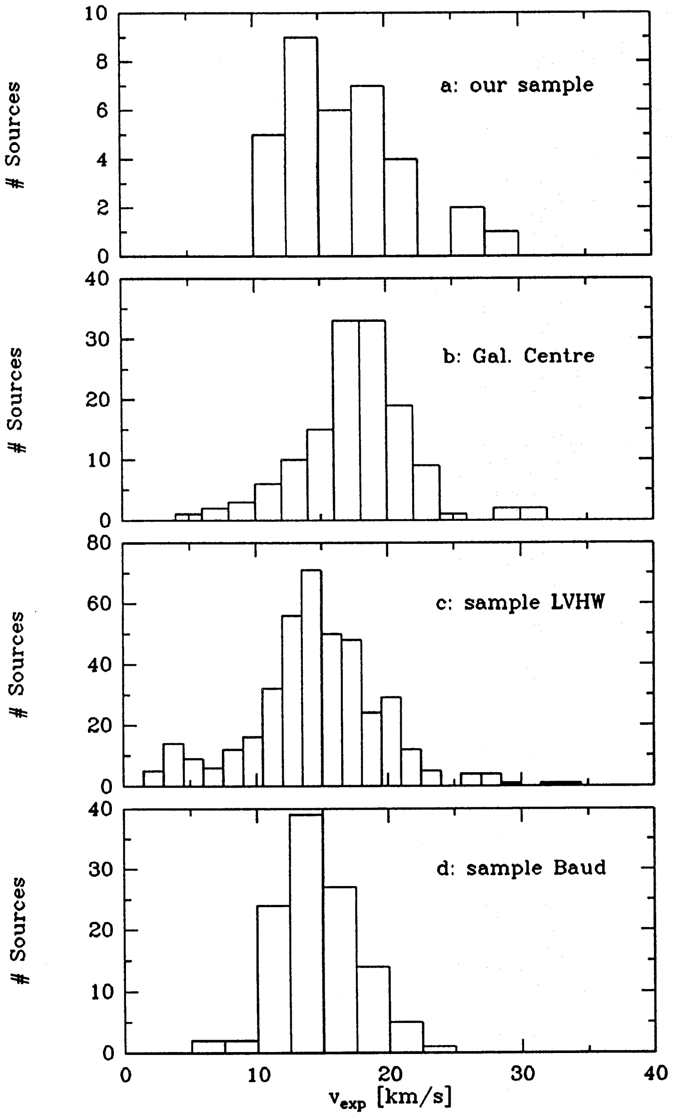

Fig. 5a–d. Distribution of expansion velocities for **a** our sample, **b** the galactic centre sample (Lindqvist et al. 1992b), **c** the LVHW sample and **d** the Baud et al. 1981 sample

star, where the OH maser operates: the luminosity of the star and the dust opacity in the shell (Jura 1986; Blommaert et al. 1993; Habing et al. 1994)):

$$v_{\rm exp} = (\chi L_*/2\pi r_{\rm in} c)^{1/2} \quad (2)$$

in which χ is the opacity of the circumstellar material, $r_{\rm in}$ ($\propto \sqrt{L_*}$) is the radius where the grains are formed and c is the speed of light.

In kinematic studies by Baud et al. (1981) and te Lintel Hekkert (1990), it has been shown that stars with small expansion velocities have larger velocity dispersions than the stars with high expansion velocities and seem to have a larger scale height above the galactic plane. The distinction is only made in a statistical sense, as in both studies the total samples are simply divided in 2 groups of equal numbers. The effect described above is plausible considering the fact that the younger OH/IR stars have higher luminosities and often have higher metallicities which lead to higher dust to gas ratios and therefore to higher opacities χ.

In our sample the expansion velocities range from ~ 10 to ~ 30 km/s (Fig. 5). The average value is 16.4 (±4.5) km/s. This is a high number in comparison with other surveys. The all-sky catalogue by LVHW has 13.6 km/s and Baud's (1981) sample of disc OH/IR stars 14.9 km/s. The latter sample was also concentrated to the plane but had a larger latitude coverage than ours. An even higher average is found for the OH/IR stars in the galactic centre (18 km/s, Lindqvist et al. 1992b). The higher average expansion velocity in our sample is in agreement with results of Baud et al. showing that high expansion velocity stars are more strongly concentrated towards the galactic plane than stars with small $v_{\rm exp}$. The same effect has been found for carbon stars by Zuckerman et al. (1986). The fact that relatively more stars with high expansion velocities are found in surveys closer to the galactic plane (with more massive and younger stars) justifies the assumption made to distinguish different "populations" on the basis of their expansion velocities. For the objects in our sample that have been identified (Sect. 3.1) this is further substantiated. One star (OH 10.077−0.095) is associated with a supergiant and two objects (OH 17.392−0.289 and OH 25.154+0.061) show very long periods in excess of 1500 days. They most likely have high luminosities (like OH 24.762−0.085 ($6.5 \times 10^4 L_\odot$)). This sort of OH/IR stars have high Main Sequence masses ($M_{\rm ms} > 3M_\odot$) and have ages of the order of $10^8 - 10^9$ yr (Iben & Renzini 1983), whereas the small expansion velocity stars are believed to be much older (≈ 10 Gyr, te Lintel Hekkert 1990). In the further analysis we will not simply divide the sample in two equal parts as was done by Baud et al. but use their median value of 14.5 km/s instead. This allows a direct comparison with their results.

4.2. Longitude distribution

The number of OH sources detected in each field individually shows significant variations as can be seen from Table 2. It seems that the number of sources does *not* increase for fields at smaller longitude, as would be expected if these sources simply follow the distribution of the thin disc (Habing 1988). The number of sources is the highest for the field at $l = 25°$. The observed distribution is in agreement with the distribution of OH/IR stars as found by Baud et al. (1981) and by Olnon et al. (1981) with their (less sensitive) single dish survey along the galactic plane. It is important to keep in mind that the sensitivity in our survey differs a bit from one field to another (Table 1). In particular the field at $l = 30°$ has a higher noise level, but because of the shallow slope of the luminosity function this hardly affects our conclusion.

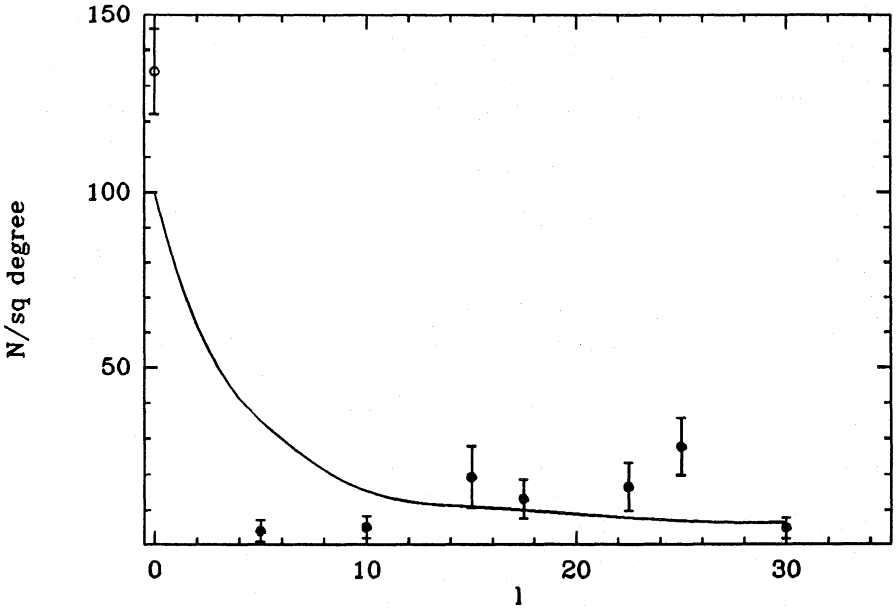

Fig. 6. The number of sources per square degree for each observed field (filled circles) and the number of sources detected by Lindvist et al. (1992a) in the galactic centre (open circle). The line shows the prediction by Dejonghe (1992) for the number of OH/IR stars in the galactic plane, based on the observed distribution of OH/IR stars selected from the IRAS Point Source Catalogue (te Lintel Hekkert 1991a)

In Fig. 6, the number of sources with a peak flux above 0.1 Jy per square degree is shown as a function of longitude. The numbers are derived by applying the correction factor for completeness (see Sect. 3.3) on the observed number of stars in each field. The errorbars reflect the $\sqrt{N}$ fluctuations of the detections multiplied by the completeness correction factors. Together with these numbers a prediction model for the number of OH/IR stars in the galactic plane (Dejonghe 1992) with the same sensitivity limit (0.1 Jy) is plotted. The model of Dejonghe is based on the sample of OH/IR stars of te Lintel Hekkert et al. (1991a) which is an IRAS based sample and thus contains mostly objects above the galactic plane. Some clear deviations from the model predictions can be observed. First there is a clear excess in the number of objects at l = 25° and to a lesser degree at l = 22.5°. Second, where the model predicts a steep increase in the number density of stars for l < 10° we find that the number of objects shows a shallow decrease until very near the galactic centre, where the number of stars rises steeply again. The number of objects there is taken from Lindqvist et al. (1992a).

Contrary to the poor comparison of our data with the predictions by Dejonghe (1992) on basis of the higher latitude OH/IR stars, we find a good agreement with the distribution of the CO gas (Burton & Gordon 1978). The molecular gas has a low density for $l \lesssim 20°$ (except for the galactic centre where the density is high) and then peaks at ≈ 25°. This latter area is called the molecular ring which is believed to be an area with a high star formation rate (Burton 1976). At 22.5 and 25 degrees we find a high number of stars (19 stars, almost half the total sample) and also high expansion velocities (14 out of the 17 stars for which the expansion velocity could be determined have $v_{\rm exp} > 14.5$) which indicates that these evolved stars are young (previous section). The low number of OH/IR stars at $l < 10°$ would indicate in the same manner that the star formation has been low in the inner region of the Galaxy. The question is for how long the star formation rate has been low in this region. Studying Dejonghe's modelling we find that the strong increase in the direction of the galactic centre is mostly due to the increase of high expansion velocity stars which are predominantly young ($\lesssim$ 1 Gyr). We thus conclude that the star formation rate inside the molecular ring has been low for approximately the last Gyr.

Due to problems of confusion and the high extinction in the inner region of our Galaxy not much is known about the structure of the stellar disc in this region. Eaton et al. (1984) performed star counts in 7 regions along the galactic plane at l = 0°, 10°, 20°, 30°, 40°, 50°, 60° at the 2.2 μm band and find similar results to ours. They demonstrate that a model with a disc and bulge structure, is not sufficient and that an extra contribution at 30° needs to be added in the form of a molecular ring. They also find that the number of objects at l = 10° is below their model prediction. They attribute it to a higher level of extinction in this direction. An effect which can not possibly influence our number counts so that we conclude that the number of stars decreases intrinsically.

4.3. Radial velocity

The stellar velocity of the OH/IR stars is derived by averaging the two peak velocities: $(v_{\rm blue} + v_{\rm red})/2$. The (l, v) diagrams of both subsamples from our survey are shown in Fig. 7. The radial velocities range from ≈ −100 km/s to ≈ 155 km/s, well in the velocity coverage of our survey (–220 to 320 km/s), indicating that it is unlikely that we missed any source at more extreme velocities. The kinematics of the OH/IR stars has been studied by several authors including Baud et al. (1981), te Lintel Hekkert (1990) and Lindqvist et al. (1991b). Using the same criterion for the expansion velocity as Baud et al., we see that the high expansion velocity sources are all situated within the boundaries defined by the HI distribution (Hartmann 1994). Only one object from the high $v_{\rm exp}$ subsample is found with negative ve-

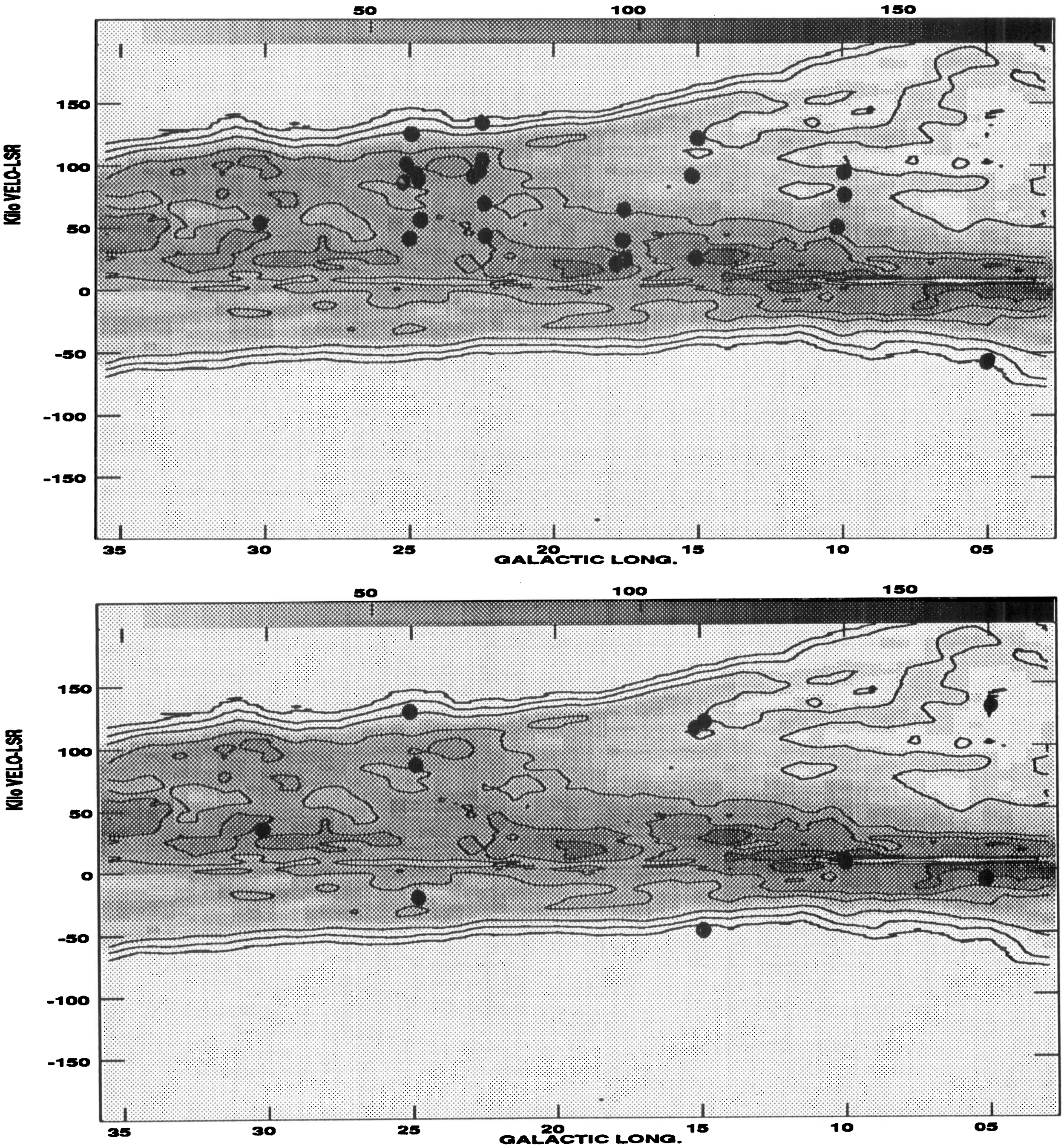

Fig. 7. The (l, v) diagrams of the OH/IR stars of our survey. The upper diagram contains the sources with $v_{\rm exp} > 14.5$ km/s; the lower diagram contains the sources with $v_{\rm exp} < 14.5$ km/s. The distributions are superposed on a grey-scale representation of the HI Brightness Temperatures in the galactic plane (the scale in units of K is indicated on top of the diagrams, Hartmann 1994)

locity; it is in the field at $l = 5°$ and may be a bulge object. The distribution certainly confirms that the high $v_{\rm exp}$ objects have a small dispersion (< 10 km/s) (Baud et al. 1981). The small $v_{\rm exp}$ sources group has a broader distribution and contains negative velocities. The velocities in excess of the maximum and minimum velocity may either indicate non-circular orbits for these stars or possibly the detection of objects outside the solar circle. In the latter case, it means that these stars are situated more than 20 kpc away from us (Burton 1988). This would rate them amongst the brightest OH/IR stars in our Galaxy.

5. Summary and conclusions

The project was set up to search for OH (1612 MHz) maser sources in the galactic plane with the VLA. In total 7 primary beam fields were examined with an automated programme and

44 objects were found. The high number of sources in each field demonstrates the necessity of using an interferometer to solve the problem of confusion. For almost 70% of the sources IRAS counterparts were found. The reason that some of the OH sources were not detected by IRAS may be that they are situated at larger distances (> 8 kpc). It is clear that the sample under study does not follow the exponential disc distribution of OH/IR stars that has been found on the basis of IRAS samples, but is very much peaked in the direction of the molecular ring (l = 25°). Also only a low number of objects were detected at l = 5° and 10°, indicating that star formation must have been low in this region for approximately the last Gyr. Most sources have high expansion velocities ($v_{\rm exp} > 14.5$ km/s). They most likely have high luminosities and high Main Sequence masses ($M_{\rm ms} > 2 - 3M_{\odot}$) and have ages of the order of $10^8 - 10^9$ yr. This is confirmed by the fact that the sources for which the OH luminosities are derived on the basis of kinematical distances are predominantly very luminous, compared to the galactic centre sample (Lindqvist et al. 1989). We confirm that the group of OH/IR stars is not a homogeneous group and that they can be divided in a younger and older group on basis of expansion velocities. The sparse survey that we have conducted demonstrates the need for observations of a large number of OH/IR stars close to the galactic plane. In particular the IRAS based searches (limited to higher latitudes) appear to provide poor constraints on the stellar distribution near the galactic plane.

Acknowledgements. The authors wish to thank Jan Melisse who kindly provided the program to search for IRAS counterparts, Harm Habing for his enthusiasm and interest in the project and Butler Burton for valuable discussions. We thank Dap Hartmann for providing us his HI data prior to publication. We acknowledge the helpful comments of the referee, Dr. P. Sivagnanam. JB acknowledges support from the Netherlands Organisation of Scientific Research (NWO) for his stay at the VLA.

References

Allen D.A., Hyland A.R., Longmore A.J., Caswell J.L., Goss W.M., Haynes R.F., 1977, ApJ 217, 108

Barcia A., Bujarrabal V., Gomez-Gonzalez J., Martin-Pintado J., Planesas P., 1985, A&A L142, L9.

Baud B., Habing H.J., Matthews H.E., Winnberg A., 1979, A&AS 36, 193

Baud B., Habing H.J., Matthews H.E., Winnberg A., 1981, A&A 95, 156

Baud B., Sargent A.I., Werner M.W., Bentley A.F., 1985, ApJ 292, 628

Becker R.H., White R.L., Proctor D.D., 1992, AJ 103, 544

Benson P.J., Little-Marenin I.R., Woods T.C., Attridge J.M., Blais K.A., Rudolph D.B., Rubiera M.E., Keefe H.L., 1990, ApJS 74, 911

Blommaert J.A.D.L., Van der Veen W.E.C.J., Habing H.J., 1993, A&A 267, 39

Burton W.B., 1976, ARA&A 14, 275

Burton W.B., 1988, in: Verschuur G., Kellerman K. (eds.) Galactic and Extragalactic Radio Astronomy. 2^{nd} ed., p. 296

Burton W.B., Gordon M.A., 1978, A&A 63, 7

Caswell J.L., Haynes R.F., 1975, MNRAS 173, 649

Cohen R.J., 1989, Rep. Prog. Phys., 52, 881

Cohen R.J., Baart E.E., Jonas J.L., 1988, MNRAS 231, 205

Cornwell T.J., Uson J.M., Haddad N., 1992, A&A 258, 583

David P., Le Squeren A.M., Sivagnanam P., 1993, A&A 277, 453

Dejonghe H., 1992. In: Weinberger and Acker (eds.) Proc. IAU Symp. 155, Planetary Nebulae. Kluwer Academic Publishers, p. 541

Eaton N., Adams D.J., Giles A.B., 1984 MNRAS 208, 241

Eder J., Lewis B.M., Terzian Y., 1988, AJ 94, 102

Engels D., 1979, A&AS 36, 337

Gaylard M.J., West M.E., Whitelock P.A., Cohen R.J., 1989, MNRAS 236, 247

Habing H.J., 1988, A&A 200, 40

Habing H.J., Tignon J., Tielens A., 1994, A&A, in press

Hartmann Dap, 1994, Ph.D. thesis, University of Leiden, in preparation

Herman J., Habing H.J., 1985, Physics Report 124, 255

Iben I., Renzini A., 1983, ARA&A 21, 271

IRAS Point Source Catalogue, 1985, U.S. Government Publication

Jewell P.R., Schenewerk M.S., Snyder L.E., 1985, ApJ 295, 183

Johansson L.E.B., Andersson C., Goss W.M., Winnberg A., 1977, A&AS 28, 199

Jones T.J., Hyland A.R., Fix J.D., Cobb M.L., 1988, AJ 95, 158

Jura M., 1986, Ir. Astron. J. 17, 322

Lada C.J., Blitz L., Reid M.J., Moran J.M., 1981, ApJ 243, 769

Lewis B.M., Eder J., Terzian Y., 1990, ApJ 362, 634

Likkel L., 1989, ApJ 344, 350

Lindqvist M., Habing H.J., Winnberg A., 1992b, A&A 259, 118

Lindqvist M., Winnberg A., Habing H.J., Matthews H.E., 1989. In Mennessier, Omont (eds.) From Miras to planetary nebulae: Which path for stellar evolution?. Editions Frontières. p. 259

Lindqvist M., Winnberg A., Habing H.J., Matthews H.E., 1992a, A&AS 92, 43

Olnon F.M., Walterbos R.A.M., Habing H.J., Matthews H.E., Winnberg A.,
Brzezińska H., Baud B., 1981, ApJ 245, L103

Sivagnanam P., Le Squeren A.M., Foy F., 1988, A&A 206, 285

Sivagnanam P., Le Squeren A.M., 1989. In Mennessier, Omont (eds.) From Miras to planetary nebulae: Which path for stellar evolution?. Editions Frontières. p. 225

Sivagnanam P., Le Squeren A.M., Foy F., Minh F.T., 1989, A&A 211, 341

te Lintel Hekkert P., 1990, Ph.D. thesis, University of Leiden

te Lintel Hekkert P., Caswell J.L., Habing H.J., Haynes R.F., Norris R.P., 1991a, A&AS 90, 327

te Lintel Hekkert P., Habing H.J., Dejonghe H., 1991b, Proc. Astron. Soc. Aust. 9, 20

te Lintel Hekkert P., Versteege-Hensel H.A., Habing H.J., Wiertz M., 1989, A&AS 78, 399 (LVHW)

Ukita N., Goldsmith P.F., 1984, A&A 138, 194

Van der Veen W.E.C.J., Breukers R., 1989, A&A 213, 133

Van Langevelde H.J., Cotton W.D., 1990, A&A 239, L5

Van Langevelde H.J., Van der Heiden R., Van Schooneveld C., 1990, A&A 239, 193

Zuckerman B., Dyck H.M., Clausen M.J., 1986, ApJ 304, 401