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High-velocity OH/IR stars at the Galactic centre

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Abstract. We present the results of a small survey for OH/IR stars at high radial velocities in the Galactic centre region performed with the VLA and the Nançay telescope. We have detected two new OH/IR stars, one at a peculiar velocity of −309 km/s, the other at −355 km/s. These two objects and one previously detected high-velocity OH/IR star (OH 0.3−0.2, Baud et al. 1975) stand out in the l, v diagram of OH/IR stars at the Galactic centre. Are these stars just on the extreme edge of the radial velocity distribution? Or are these objects no longer bound to the Galactic centre? We discuss these possibilities, showing that these are most likely bulge stars on elongated orbits passing close to the Galactic centre.

Key words: stars: OH/IR – radial velocities – Galaxy (the): center of – Galaxy (the): bulge of – Galaxy (the): kinematics and dynamics of

1. Introduction

Surveys of OH/IR stars are now regularly used to study stellar dynamics (e.g. te Lintel Hekkert et al., 1991). A sample of 134 OH/IR stars is known at the Galactic centre from a survey with the VLA[1] (Lindqvist et al. 1992a). These stars were found by their maser emission in the 1612 MHz OH line. Accurate positions ($\leq 1''$) and velocities (≈ 1 km/s) were obtained, so these data are suited to study the kinematic behaviour of evolved stars around the Galactic centre (Lindqvist et al. 1992b). The survey was limited in sensitivity and covers the inner 100 pc and a limited range of velocities. Here we address the question whether this limited velocity range has influenced the results of the survey.

The original observations were performed with a bandwidth of 3×781.25 kHz, corresponding to a total range from –217 to +217 km/s. From the l, v diagrams it was suspected that few stars were missed; the detection rate dropped substantially towards the edges of the band. On the other hand, a high-velocity OH/IR star had been detected previously as a serendipitous result in a single dish survey (Baud et al. 1975; Baud et al. 1979). OH 0.3–0.2 (or Baud's star) is observed at a $v_{\rm lsr}$ of –342 km/s.

The original Lindqvist et al. (1992a) survey had to be performed with an interferometer for two reasons. First there is confusion, because in a single primary beam of the VLA one finds up to 60 objects. For a single-dish telescope this implies that the combined spectrum of about 60 sources is observed, and it is generally not possible to disentangle the resulting spectrum. Secondly there is strong background continuum emission against which interstellar 1612 MHz absorption is seen (e.g. Habing et al. 1983). An interferometer is able to resolve this extended structure and detect the point–like emission of the OH/IR stars. These considerations are of no importance in the search for high-velocity OH/IR stars. The number of sources will be less at the velocities considered here and no contribution from interstellar OH is expected (e.g. Boyce & Cohen 1989). Thus the high-velocity sources can be found with single dish telescopes.

In Sect. 2 we describe single dish observations carried out with the Nançay telescope. Part of the area observed was also covered by new VLA observations, which confirmed our results and yielded accurate positions. We present the results in Sect. 3 and give a brief discussion on the dynamical origin of these high-velocity stars.

2. Observations

We used the radio telescope at Nançay (France) during two observing runs: 10 days in October 1990 and 15 days in July/August 1991. The telescope is a transit instrument, consisting of two large "fences"; the receiver is mounted on a train that moves through the focal plane. The telescope has a large collecting area, equivalent to a 100 m telescope, but the configuration gives rise to a rather poor beam. Not only is the beam quite elongated (3.5 by 18 arcmin FWHM at 1612 MHz), but also the sidelobe level is high, making the observations vulnerable to interference from the sky. At 1612 MHz the GLONASS satellites are a major source of such problems.

The telescope is equipped with a flexible correlator spectrograph with 1024 channels. We used the system to switch in frequency between bands on extreme positive and negative velocities. The bandwidth was 3.2 MHz, yielding a velocity coverage of ±149 to ±744 km/s, with a resolution of 1.2 km/s in two circular polarisations. The intermediate velocities are left out, because here considerable spectral signature is expected, as described above. The switching technique produced a bandpass of poor quality in this case. The frequency switching is

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

Fig. 1. Sky and velocity coverage of the survey. Solid lines indicate area covered by Nançay observations, short dashed lines indicate the new VLA observations, while long dashed lines are the original Lindqvist et al. (1992a) fields. OH/IR stars from the Lindqvist et al. (1992a) sample are represented by open symbols and the three high-velocity objects by filled symbols.

over too large a bandwidth especially with the bright emission from the Galactic centre in the beam and the telescope being quite sensitive to interference. However, the OH/IR stars are relatively easy to recognize amongst residual ripples in the spectra. The masers have very sharp spectral features and normally have a recognisable double peaked signature. Unfortunately the Nançay receiver system also produces some sharp spurious features in the spectra, which are due to cross-talk of the LO system or the clock frequency of the correlator. Thus we need to treat our results carefully.

Two detections were made in the first observing run. We used the VLA in order to check these and to get accurate positions for these sources. In a two hour observing run 26 telescopes were pointed at a position of $\alpha_{1950} = 17^{\rm h}42^{\rm m}30^{\rm s}$, $\delta_{1950} = -28°59'00''$ and at two different velocity settings, both of 1.5625 MHz bandwidth and divided into 256 channels centred on $v_{\rm lsr} = \pm$ 300 km/s, yielding a total coverage of ±177 −±402 km/s. At the beginning of the run 3C286 was observed as a primary flux calibrator. 1748-253 was used as a secondary calibrator. The data reduction was carried out as described in Van Langevelde et al. (1992b), and included visibility based continuum subtraction (Van Langevelde & Cotton 1990).

After calibration, data cubes were constructed of 512^2 pixels of 4 arcsec and 256 channels of 1.1 km/s. Because the VLA was in the C array this covers the entire primary beam (14′ for a factor 2 attenuation). These cubes were searched in a systematic way, with a method that checks every position for a combination of pixels that exceed several times the noise in the maps. All spectra with possible detections were then carefully inspected, as well as the corresponding maps.

Fig. 2. Spectra of the newly detected OH/IR stars, as observed with the VLA

Table 1. Positions and fluxes for the new detections

Name	Position (1950)		v [km/s]	F [Jy]
OH 359.837+0.120	$17^{\rm h}41^{\rm m}35.12^{\rm s}$	$-28°59'31.3''$	−374	0.17
			−336	0.21
OH 359.918−0.056	$17^{\rm h}42^{\rm m}27.87^{\rm s}$	$-29°00'56.0''$	−328	0.78
			−290	0.09

3. Results

In Fig. 1 we show the total sky and velocity coverage of our survey, together with known OH/IR stars from Lindqvist et al. (1992a). The two possible detections of the first Nançay run were confirmed with the VLA; the Nançay and VLA profile shapes, velocities and fluxes are identical. In Fig. 1 these two new sources are shown, together with Baud's star (positional information from van Langevelde et al. 1992a), which we treat here as an object with comparable characteristics.

In table 1 we list the positions and fluxes for the new detections. The spectra are given in Fig. 2. In the generally accepted models for OH/IR stars the velocity of the underlying star is calculated as $v_\star = (v_{\rm blue} + v_{\rm red})/2$, because the peaks originate from the back and front of an expanding shell (see Herman & Habing 1985, for a review).

It turned out that the source OH 359.918−0.056 was detected previously in the infrared. At the same position Rieke & Rieke (1988) find a star at a velocity of −314 km/s (object # 40 in their table 1, although they have some reservations about this object). We thus confirm their observation, in particular the measurement of the velocity of this source using the CO band head.

We completed the search for more objects covering the area indicated in Fig. 1. The detection limit for these regions is not uniform. First, there are differences between limits of individual Nançay observations, because of differences in effective integration time, mostly due to interference. A typical value for the noise at Nançay is 70 mJy, corresponding to a detection limit of ≈ 250 mJy. For the VLA beam the sensitivity drops by a factor of two at the edge of the beam. Both the fields at positive and negative velocity were searched in a systematic way for sources brighter than 150 mJy. No further detections were made.

We cannot be sure that we have detected all high-velocity OH/IR stars at the Galactic centre. First, we have not obtained full sky coverage. Second, the flux limit is not sufficient to detect all OH/IR stars at the Galactic centre. The luminosity function of the original survey shows that the number of stars

Fig. 3. Radial velocities as a function of projected distance from SgrA*. The OH/IR stars from the Lindqvist et al. (1992a) sample are indicated by open symbols and the high-velocity stars by filled symbols. Also drawn is the estimated circular velocity from Lindqvist et al. (1992b)

is still increasing at the detection limit (Lindqvist et al. 1989). The sensitivity in our VLA field is comparable to the Lindqvist et al. (1992a) survey.

4. Discussion

4.1. Kinematics

We find that high-velocity stars towards the Galactic centre exist, but that the bulk of the OH/IR stars indeed lies in the velocity range covered by the Lindqvist survey.

All three detected sources have velocities between –300 and –400 km/s. One of the stars is rotating opposite to Galactic rotation. One wonders why no sources at high positive velocities were found, because these velocities were searched with exactly the same sensitivity. However, the chance to find the same sign for the radial velocity of three out of three high velocity stars is still 25%. So we will not consider this as significant in the interpretation. Furthermore no absolute velocities above 400 km/s were found, although the Nançay observations were sensitive for velocities up to almost 750 km/s. In the discussion we should bear in mind that we have no information on the two components of the stellar velocities in the plane of the sky.

We show in Fig. 3 the radial velocities of the sample with distance from SgrA*. The inferred circular velocity as a function of projected radius as calculated by Lindqvist et al. (1992b) is plotted in the same diagram. The flat rotation curve in Fig. 3 corresponds to a density distribution proportional to r^{-2}, as is generally used for the inner Galaxy. For this potential an escape velocity can only be calculated for a finite extent of this mass distribution, but we can estimate how far a star can travel radially. We use the observed radial velocity as a lower limit for the total velocity and the projected distance as a lower limit for the actual distance from the Galactic centre and estimate that Baud's star will travel to 3.2 kpc in the r^{-2} potential. The values for the other two stars are 2.1 and 0.5 kpc. This does not imply that these stars will necessarily reach such galactocentric radii; beyond ≈ 1 kpc for instance, the circular velocity in the Galactic disk is higher, indicating a potential that would slow down the outward motion.

Before discussing the dynamical origin of these stars, we consider a number of issues. First the number of high-velocity stars is at least several percent (≥ 3 out of 134). Not only is the sensitivity limit and sky coverage of our high velocity survey less than the Lindqvist et al. (1992a) survey, but we should also bear in mind that we can only distinguish stars that have a large velocity in our line of sight. Inspection of the l, v diagrams in Lindqvist et al. (1992b) shows that maybe up to 10% of the sources show deviating velocities (e.g. OH 359.4+0.8 from Habing et al. 1983).

Even a few percent is a large number, because, although the OH/IR phase is short, most stars may go through the phase and hence each OH/IR star represents a large number of stars in different evolutionary stages. This suggests that a few percent of all stars in the centre have high velocities. For the solar neighbourhood we can estimate the total mass contained in stars per OH/IR star. Herman & Habing (1985) and Jura & Kleinman (1989) give values for the local OH/IR star density. We use Mihalas & Binney (1981, p. 222) for a description of the stellar content of the solar neighbourhood and find $\approx 10^6 M_\odot$ for every observed OH/IR star. This ratio might be less in the bulge, because a larger fraction of the bulge stars may have reached the AGB phase. The value of $10^6 M_\odot$ per OH/IR star is roughly consistent with the fact that from the dynamics of the Lindqvist sample (of 134 objects) the presence of several times $10^8 M_\odot$ is inferred, which is in agreement with other studies.

4.2. Possible explanations for the high-velocity stars

We consider three different possibilities to explain the presence of high velocity stars. First we can ask whether these stars can be at the tail of an isotropic gaussian velocity distribution of a nearly round stellar population. Our detections then correspond to the stars which happen to move in the line of sight. The second hypothesis is that these stars are shot away from the Galactic centre, in a star – binary collision or a collision of a binary star with the central black hole, during which the binary is split up; one star is bound to the black hole the other is ejected at high velocity. The third idea is that these are bulge stars on elongated orbits that pass through the Galactic centre region.

We rule out the first option. Because the observed stars are all at 3 times the circular velocity (at least), or at more than 3 times the velocity dispersion, we can reject the hypothesis that they are drawn from an isotropic population at 99.4% confidence level (assuming a gaussian distribution).

Next we consider collision mechanisms. The first problem with this hypothesis is that there is no straightforward reason why these collisions would not result in velocities higher than the observed 350 km/s. For the collisions we estimate the rate at which stars are ejected from the Galactic centre. We calculated the "lifetime" of the high-velocity stars as 3×10^5 yr, after that they will have travelled out of the inner 100 pc region. Thus with the ratio of $10^6 M_\odot$ per OH/IR star we require an ejection rate of 10 $M_\odot$/yr. This cannot be provided by collisions between single stars and binaries, not even in the inner Galaxy. We therefore estimate the cross section for binary – black hole collisions, assuming a black hole mass of less than $10^7 M_\odot$ (McGinn et al. 1989; Sellgren et al. 1990).

This mechanism was explored before by Hills (1988) who showed that one expects a hyper-velocity star ($v > 1000$ km/s) once every 10^3 yr from the collision of a tight binary ($r_{\rm bin} \leq 0.1$ AU) with a $10^6 M_\odot$ black hole. For a collision that results in an escaping star with a speed of 300 km/s, the condition for the binary is less tight ($r_{\rm bin} \approx 1$ AU). This implies a larger tidal disruption radius around the black hole (of the order of 10^{-2} pc) and thus a larger cross section. Even with a large correction for gravitational focusing and a large fraction of stars in close binaries we find a collision rate that is more than three orders of magnitude too small. This has a very weak dependence on the mass of the black hole. Moreover, when binaries are destroyed, a fraction of the binary masses is swallowed by the black hole. The energy production and the upper limit on the mass of the black hole are also grossly inconsistent with a collision rate of 10 $M_\odot$/yr.

Finally, we consider the possibility that the three high-velocity stars are bulge stars on orbits of very small angular momentum. This takes them through the inner 100 pc at high velocity. A star on a nearly radial orbit that takes it out to the above mentioned radii of a few kpc spends somewhat less than 1% of the orbital period inside the observed projected radii. Most of the time is spent at large radius and low velocity. By our earlier estimate of $10^6 M_\odot$ per OH/IR star, the observed high-velocity OH/IR stars would then correspond to a total of several times 10^8 stars on such elongated orbits. We point out that this explanation is not valid if further studies show that there are significantly more high velocity stars with negative radial velocities.

Starcounts as well as the kinematics of the atomic and molecular gas in the central kpc of the Galaxy indicate that the potential is not axisymmetric. This may be caused by a flat bar or a triaxial bulge with axis ratios of about 1 : 0.85 : 0.6 (Binney et al. 1991; Weinberg 1992). This can produce a strongly non–gaussian velocity distribution (Statler 1987). Hunter & de Zeeuw (1992) show that 20–40% of all stars in such a triaxial bulge must be on box orbits. These have large radial extent in the direction of the long axis of the bulge, and they all pass very close to the centre. With a total number of bulge stars of the order of 10^{10}, this mass fraction is roughly consistent with the number of observed high–velocity OH/IR stars. However, for this interpretation to be valid, the long axis of the bulge must point in a direction close to the line of sight to the Galactic centre, so that the tail of the non–gaussian velocity distribution can be observed in the velocity component along the line of sight. Although the orientation of the triaxial bulge is not known very accurately at present, Binney et al. (1991) present strong evidence that we observe the bulge at a viewing angle of only 16 degrees from its long axis. We conclude therefore that the observed high-velocity OH/IR stars are consistent with the bulge being triaxial.

5. Conclusions

We have shown that the Lindqvist et al. (1992a) survey is not significantly biased towards low absolute velocities, although two high-velocity objects were found. We have shown that the three known high-velocity stars trace a different population than most of the stars in the original survey. We show that it is unlikely that we witness here the ejection of stars from the Galactic centre. The observed velocities and numbers can however be consistent with a, fractionally large, population of bulge stars on orbits of very low angular momentum.

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