Baud's star and high–negative velocities in the Galactic center

Lorant Sjouwerman (National Radio Astronomy Observatory)

ABSTRACT:

Almost three decades ago, in a survey for OH masers in the Galactic center, Baud et al. (1975) detected an OH/IR star with a blue-shifted (negative) line-of-sight velocity of 343 km s^{-1} with respect to the Local Standard of Rest, 25′ from Sgr A* (50 pc in projection). Since then, at least three more high-velocity ($|V| > 250$ km s^{-1}) OH/IR stars have been found within about 12′ of the Galactic center (25 pc in projection), all with a negative velocity.

Several authors have also found emission and absorption by high-negative velocity gas (HI, H2CO, HCO$^+$, CO, OH) toward the Galactic center; gas with $|V| > 180$ km s^{-1}.

This contribution attempts to explain the observations of the high-negative velocity OH/IR stars by relating them to the observations of the high-negative velocity gas.

Introduction:

While performing a survey for OH sources in the direction of the Galactic center (GC), Baud et al. (1975) observed a double peaked 1612 MHz OH absorption feature in a frequency switched observation. Further analysis showed that this absorption feature was actually a double peaked emission feature in the reference band. As the double peaked profile is characteristic for OH/IR stars, this star therefore had to be at high velocity (HV), with a line-of-sight velocity of about −340 km s^{-1}.

Although it was know that high velocities (up to ±200 km s^{-1}) are not uncommon in the direction of the GC, the authors already remarked that the star is far outside that range. Another striking characteristic is that the object seems to be moving counter to the Galactic rotation.

In subsequent papers where they analyzed their results, it was derived that HV stars should be uncommon (Baud et al. 1979), and that a (high) negative velocity due to a star outside the Solar circle to explain the observation was unlikely (Baud et al. 1981).

Highly elongated elliptical orbits:

About ten years later, in 1992, van Langevelde et al. published the detection of another two HV OH/IR stars. They are located even closer to the GC, within 12′, and also appear at negative line-of-sight velocities of about −300 to −350 km s^{-1}, both moving with Galactic rotation. No OH/IR stars were found at the similar observed high-positive velocities.

Having three negative high-velocity (NHV) OH/IR stars among about 150 (from a survey by Lindqvist et al. 1992), the authors were able to distinguish between some possible explanations.

As the possibility of finding three NHV stars with the same sign is 25%, they did not consider this as important. However, they noted that ≥3 NHV stars is a few percent, which is too high to be explained by a HV tail of an isotropic velocity distribution, and that collision mechanisms would produce velocities higher than the limit of 350 km s^{-1} observed.

They concluded, under restriction that not more negative HV stars were found without finding positive HV stars, that HV stars were consistent with highly elongated orbits, along the line of sight in a tri-axial bulge.

High-velocity gas:

Two decades ago, Güsten & Downes (1981) pointed out that, toward the radio continuum of the GC, absorption by H2CO and HI gas was seen at a velocity around −190 km s^{-1}. Furthermore they remarked that this velocity exceeds the velocity range of the known components, that the gas must be in front of the GC, and that equilibrium rotation about the nucleus could be ruled out (unless the center of rotation was shifted ≥10′ away from the nucleus). They favored an "ejection" model after they argued against a large scale foreground "field" model.

About ten years later, Marr et al. (1992) suggested that some of the HNVG interacts with the GC environment, whereas Pauls et al. (1993) proposed the HNVG close to the GC to be falling inward from behind.

In 1993, Liszt & Burton discussed the observation of Marr et al. (1992) and Pauls et al (1993) that Sgr A* was not found to be occulted by the high-negative velocity gas (HNVG), and argued that the HNVG was a foreground cloud and unrelated to the phenomena in the GC. They mainly based this on their CO emission mapping of the HNVG, which showed an elongated East-West structure West of Sgr A* with a very small velocity dispersion across the feature, and which is suspiciously parallel to the rotation axis of the Circumnuclear disk, as well as to the emission of the near side kiloparsec scale 'expanding' molecular gas.

Many papers followed with different tracers and on different angular scales in which the physical association between the HNVG and Sgr A* with its direct environment was investigated (e.g. Yusef-Zadeh et al. 1993; Marshall & Lasenby 1994; Yusef-Zadeh et al. 1995; Liszt & Burton 1995; Zhao et al. 1995; Roberts et al. 1996; Sofue 1996).

Arguments in 'favor of this', and arguing 'against that' went back and forth, and it probably now should be accepted that the HNVG and the GC do interact, in particular at a location a few arcminutes to the South-West of Sgr A*. The HNVG has been modeled as gas on a tilted hyperbolic orbit about Sgr A*, where the gas is tidally disrupted within the central 100 pc and is flowing toward the nucleus from the far side (Zhao et al., 1995; Roberts et al., 1996).

However, none of the authors related the NHV stars and the HNVG.

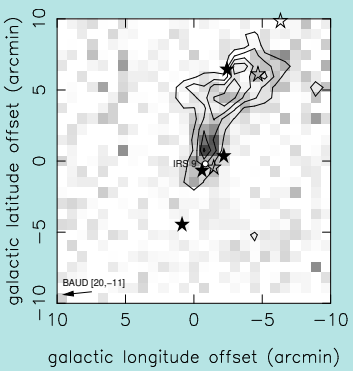

Figure 1:

Galactic sky distribution of NHV OH/IR stars, IRS 9 (Reid et al 2003) and HNVG (here the ^{12}CO gas; Liszt & Burton 1993). Offsets are with respect to Sgr A*. The arbitrary contours (gray-scales) outline the HNVG with a velocity of −190 (−213) km s^{-1}. The NHV stars at a velocity of around −320 (−150) km s^{-1} are the open (closed) symbols. Comparison with other HNVG, for example HI absorption (Yusef-Zadeh et al. 1993) or 1667 MHz OH absorption (Karlsson et al., in preparation), shows a similar picture. Modified from Sjouwerman (1997).

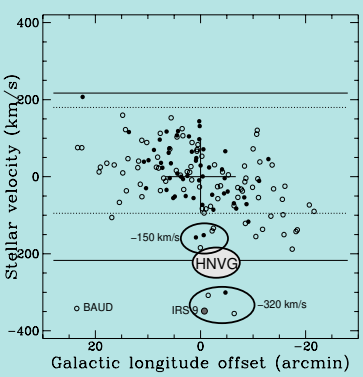

Figure 2:

Galactic velocity distribution of OH/IR stars (Sjouwerman et al. 1998) and IRS 9 (Reid et al 2003). The NHV OH/IR stars with a Galactic longitude between ±5′ of Sgr A* and with velocities around −320 km s^{-1} clearly stand out (open symbols in Fig. 1), as well as the −150 km s^{-1} stars (filled symbols in Fig. 1). The circles are the OH/IR stars known prior to the Sjouwerman et al. (1998) survey. The spatial and velocity structure of the HNVG nicely fits into the diagram between the −320 km s^{-1} and −150 km s^{-1} groups. Modified from Sjouwerman (1997).

Associating the NHV stars and HNVG:

In a deep OH survey, Sjouwerman et al. (1998; Sjouwerman 1997) found another HV OH/IR star, again at a negative velocity of −301 km s^{-1}. Actually, the new NHV OH/IR star appears almost exactly in the line connecting the two NHV stars of van Langevelde et al. (1992) in the sky plane. This alignment still holds when another NHV star (IRS 9) at −346 km s^{-1} is included, a NHV star reported by Menten & Reid (1998, in their figure; Reid et al. 2003). Finding more, negative-only HV stars in the velocity range −300 to −350 km s^{-1} clearly undermines the tri-axial bulge NHV explanation by van Langevelde et al. (1992).

Investigating the striking spatial alignment of the NHV stars, Sjouwerman (1997) for the first time linked the observations of the NHV stars to the observed HNVG (Figure 1). It turned out that the large scale HNVG distribution, as well as the NHV stars (including IRS 9), lie in a plane with the same inclination with respect to the Galactic plane, and which does not intersect with the position of Sgr A* itself (but South-West of it). Moreover, the velocity structure of the HNVG also aligns with the velocities of the NHV stars and the unbound IRS 9 (Reid et al. 2003) in the longitude-velocity diagram (Figure 2).

The emerging picture:

Recalling the explanation of the HNVG with an inclined hyperbolic orbit by Zhao et al. (1995) and Roberts et al. (1996), it seems not difficult to also explain the NHV stars with this model. Picturing that the gas and stars are falling in from a positive longitude somewhere (North-)East and behind the GC, on an inclined orbit with the periastron South-West of Sgr A* and along the line of sight, the gas is gravitationally more easily influenced by the GC than the stars, giving rise to a hyperbolic appearing x_1-to-x_2 transition of the orbit and the interactions of the HNVG in the inner few pc. The unbound heavy stars are hardly deflected, nor decelerated and continue almost in a straight line, i.e. more to the South (more negative longitudes) of the HNVG. It would explain the constant velocities of the NHV stars, their location with respect to the GC and HNVG, the bound stars at −150 km s^{-1} (that may have decelerated and thus follow the HNVG closer), and the asymmetry of lacking positive HV components. That the gas and stars have a similar inclination as the rotation axis of (but offset from) the Circumnuclear disk and the kpc-scale radio lobe (Sofue 1996) is coincidental, but the 1720 MHz OH masers at +60 km s^{-1} (Yusef-Zadeh et al., 1996; 1999) that also line up in this plane might result from the deflected gas.

Baud's star:

Ironically, this explanation does not directly solve the high-velocity problem posed by Baud's star, the star that triggered one to start thinking about this problem three decades ago. Possible solutions that all can explain the retrograde circular motion and the deviation from the straight alignment with the HNVG and other NHV stars:

- Baud's star resulted from totally unrelated single event, e.g. such as the collision mechanism described by van Langevelde et al. (1992).
- Baud's star falls in from the other side, indeed having an opposite orbital angular momentum. This would agree with the velocity of the other NHV stars, but one would expect a better alignment in the plane of the sky.
- Baud's star got deflected by Sgr A*, but still moves almost in the line of sight. This would agree with the misalignment (to the proper side of Sgr A*) with the other NHV stars, and may be indicated by the HNVG East of Sgr A* as observed by Yusef-Zadeh et al. (1993, their Fig. 2).
- Baud's star lags in a similar orbit still on the other side of Sgr A*. This would explain the difficulty of finding a red counterpart (Blommaert et al. 1998) and is consistent with a periastron South of Sgr A*.

References:

Baud et al, 1975, Nature **258**, 406
Baud et al, 1979, A&AS **35**, 179
Baud et al, 1981, A&A **95**, 171
Blommaert et al, 1998, A&A **339**, 991
Güsten & Downes 1981, A&A **99**, 27
Lindqvist et al, 1992, A&AS **92**, 43
Liszt & Burton 1993, ApJ **407**, L25
Liszt & Burton 1995, ApJS **98**, 679
Marr et al, 1992, ApJ **400**, L29
Marshall & Lasenby 1994, MNRAS **269**, 619
Menten & Reid, 1998, ASP Conf. Ser, 144 IAU Colloq. **164**, 229
Pauls et al, 1993, ApJ **403**, L13
Reid et al, 2003, ApJ (astro-ph/0212273)
Roberts et al, 1996, ApJ **459**, 627
Sjouwerman 1997, thesis **Onsala**, Sweden
Sjouwerman et al, 1998, A&AS **128**, 35
Sofue 1996, ApJ **459**, L69
van Langevelde et al, 1992, ApJ **396**, 686
Yusef-Zadeh et al, 1993, ApJ **410**, L27
Yusef-Zadeh et al, 1995, ApJ **442**, 646
Yusef-Zadeh et al, 1996, ApJ **466**, L25
Yusef-Zadeh et al, 1999, ApJ **512**, 230
Zhao et al, 1995, ApJ **450**, 122