RevMexAA (Serie de Conferencias), **15**, 20–22 (2003)

DYNAMICS OF THE MOLECULAR JETS IN THE ARCHETYPICAL PREPLANETARY NEBULA, IRAS 16342−3814

M. R. Morris,[1] R. Sahai,[2] and M. Claussen[3]

RESUMEN

Que los chorros fuertes puedan lanzarse en las etapas muy tempranas de las nebulosas preplanetarias no tiene mejor evidencia que en la clase de "nebulosas fuente de agua": sistemas en los cuales los máseres de H_2O de muy alta velocidad están ubicados a lo largo del eje polar. El miembro más extremo conocido de esta clase es IRAS 16342−3814 que tiene emisión de maser de H_2O a velocidades radiales de $\pm 160\,\mathrm{km\,s^{-1}}$ relativas a la velocidad sistémica central. Por lo tanto, esto impone las restricciones más fuertes sobre la regulación y cinemática de los chorros dirigidos desde los polos de tales sistemas. En este trabajo describimos esta clase de objeto y reportamos los primeros resultados de nuestro estudio de los máseres de agua en IRAS 16342 hecho con el VLBA. En este estudio, todavía en progreso, los movimientos propios de los máseres, junto con sus velocidades radiales, deben proporcionarnos una idea bastante completa de la evolución de la dinámica de los chorros.

ABSTRACT

That strong jets can be launched at very early stages in preplanetary nebulae is nowhere better evidenced than in the class of "water fountain nebulae": systems in which very high-velocity H_2O masers occur along the polar axis. The most extreme member known in this class is IRAS 16342−3814, which displays H_2O maser emission at radial velocities of $\pm 160\,\mathrm{km\,s^{-1}}$ relative to the central, systemic velocity. It thus places the strongest constraints on the timing and kinematics of the polar outflows in such systems. Here, we describe this class of object, and report on the first results from our VLBA study of water masers in IRAS 16342. In this ongoing study, the proper motions of the masers, when combined with their radial velocities, should eventually provide a rather complete picture of the evolution of the jet dynamics.

Key Words: **ISM: JETS AND OUTFLOWS — PLANETARY NEBULAE — STARS: MASS LOSS — STARS: POST-MAIN SEQUENCE**

1. BACKGROUND

Bipolarity—the presence of two diametrically opposed lobes, usually with an equatorial "waist" of high extinction between them—is a common feature of the reflection nebulosity around post-AGB stars, and yet its cause is still undetermined. Mechanisms which have been considered include: (1) shaping of the outflowing wind by the gravitational field of a binary companion (Morris 1981, 1987; Mastrodemos & Morris 1999), (2) dynamical forcing by a strong, stellar magnetic field (García-Segura et al. 1999), or (3) sculpting of a prior, more spherically symmetric outflow by wandering and/or episodic jets (Sahai & Trauger 1998; Soker 2002). Some combination of these mechanisms (e.g., Soker & Rappaport 2000) may be necessary for a complete accounting of bipolarity, but one of the strongest constraints on the mechanism responsible is set by the timing of its observable onset. In some cases (e.g., V Hydrae, OH 231.8+4.2, and IRAS 09361+1212) pronounced bipolarity appears very early in post-AGB evolution, even while the central star is still on the AGB. We appeal to such early systems in order to shed light on the mechanism responsible for bipolarity, presuming that the evidence there will be least confused by subsequent evolutionary events.

One remarkable class of objects which falls in this early category, and which has received relatively little attention, is the "water fountain" class of bipolar nebulae, characterized by having extremely high velocity H_2O maser emission arising along the system's polar axis. Other characteristics include an obscured, presumably late-type central star, rapid variability of the water maser emission, and very broad, main-line OH maser emission (Likkel, Morris, & Maddalena 1992). While there are currently only 3 confirmed members of this class of object (IRAS 16342−3814, IRAS 19134+2131, and W 43A), there are a number of potentially closely related stars for which high-velocity H_2O emission remains un-

[1]Department of Physics and Astronomy, UCLA, USA.
[2]Jet Propulsion Laboratory, Pasadena, USA.
[3]National Radio Astronomy Observatory, Socorro, USA.

reported, possibly because the maser geometry is unfavorable (e.g., OH 231.8+4.2, IRAS 15405−4945, He 3-1475, and IRAS 18491−0207, all of which have very broad OH main-line emission; te Lintel Hekkert & Chapman 1996).

Several important clues to the nature of the H_2O masers in these sources have arisen. First, the H_2O masers in W 43A, which are strongly separated along the system's polar axis (Diamond & Nyman 1988), show rapid proper motions indicating expansion from the center, and the velocity vectors suggest that the velocity field deviates slightly from axisymmetry in the sense of being point reflection symmetric (Imai et al. 2002). Second, there is an apparent pairing of the many individual velocity components in the sense that most of them noted in a monitoring project have counterparts that are symmetric about the systemic velocity, and typically located hundreds of km s^{-1} away in the spectrum (Likkel et al. 1992). This is the kinematical aspect of point reflection symmetry. It strongly suggests that, when collimated outflows are launched, presumably near the polar axis, diametrically opposed blobs, jets, or gusts are simultaneously emitted, and they have very similar effects on the ambient circumstellar envelope. We conclude that the point reflection symmetry of the high-velocity outflow is not merely a stochastic effect applying only to the large-scale morphology of the nebula, but is respected in minute detail.

The prevailing paradigm for the nature of the water fountain masers is that they arise in post-shock regions where the polar jets strike the ambient, slow-moving, circumstellar material expelled during a prior stage of more-or-less spherically symmetric mass loss. The masers are often observed as linear arrangements of maser spots, reflecting the orientations of the edge-on shocks.

2. IRAS 16342−3814

The most extreme of the water fountain nebulae, IRAS 16342 has water masers spread over more than $320\,\mathrm{km\,s^{-1}}$. The main-line OH masers cover at least half of this velocity range (Likkel & Morris 1988; te Lintel Hekkert & Chapman 1996). The pronounced bipolarity of this object was evident in the *Hubble Space Telescope* (*HST*) image published by Sahai et al. (1999), reproduced here in Figure 1. The locations of OH emission spots superimposed on the nebula illustrate what is probably a close physical relationship between the nebular lobes and the OH emission. Because the OH maser features most tightly confined to the polar axis have the highest velocities, we conclude that the outflow velocity increases continuously from the equatorial plane to the poles in this system. Thus, the H_2O masers, with the highest velocities by far, are expected to lie close to the polar axis.

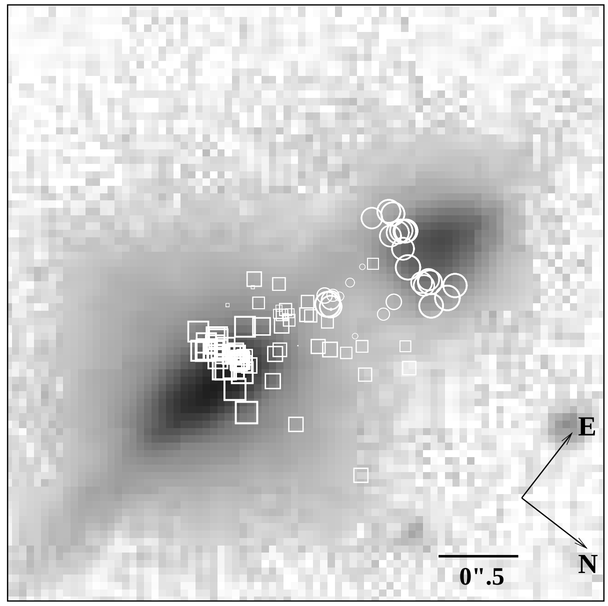

Fig. 1. 0.8 μm image of IRAS 16342−3814 (log stretch), made with the WFPC2 camera on *HST* (adapted from Sahai et al. 1999). The symbols represent the locations of OH masers and the symbol size represents the velocity offset from the systemic velocity. The squares (circles) correspond to blue (red) shifted emission.

3. OBSERVATIONS OF H_2O IN IRAS 16342

IRAS 16342 was observed with the VLBA and VLA during 6 epochs between 2002 February and July. Here, we report on the locations of the masers relative to the nebula. The proper motions will be reported elsewhere.

The observed maser spots are spread out over $> 2''$ (or $4000\,\mathrm{AU} \times D/(2\,\mathrm{kpc})$, for source distance D). Figure 2 shows a plot of the locations of the maser spot groups, and the velocities of each spot group. All of the maser emission clearly arises relatively near the polar axis of the system, although it occurs in well separated groups, presumably representing different episodes of mass ejection in slightly different directions.

When examined in detail with the 1 milliarcsecond beam of the VLBA, the clusters of maser spots at the most extreme velocity ranges (between -62 and $-68\,\mathrm{km\,s^{-1}}$ on the blue side and between 171 and $184\,\mathrm{km\,s^{-1}}$ on the red side) are seen to be

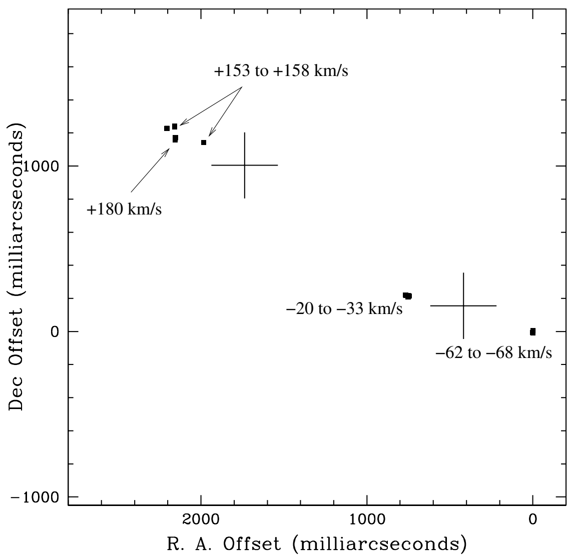

Fig. 2. Schematic showing the locations of the H_2O maser clusters in IRAS 16342−3814, as measured with the VLBA during 2002 Feb. The radial velocities are indicated. Crosses mark the brightness peaks of the optical lobes.

arrayed in quasi-linear strings oriented roughly perpendicular to the polar axis (not resolved in Fig. 2). This is what one would expect from the edge-on, planar shock structure that would arise as a collimated jet impacts the ambient, slow-moving circumstellar outflow. As molecules form, or reform, in the post-shock region (cf. Glassgold, Mamon, & Huggins 1991), the masers adopt a planar geometry (Elitzur, Hollenbach, & McKee 1992).

4. PERSPECTIVE

The objects in the "water fountain" class give us a wonderful tool for following jet orientations in real time, allowing us to address the question of how they evolve. In particular, are the jets really precessing, or is the distribution of directions stochastically distributed within a narrow range of solid angles?

Another important question is, how long does the water fountain phase last? The expansion timescale for the masers is only 30 to 100 years, and given the small number of known objects in this category, the overall timescale for this phase may be on the order of only 10^3 years. However, Miranda et al. (2001) have recently shown us that water fountains can persist into the planetary nebula stage, albeit with much reduced velocities in the case of the planetary nebula K 3-35.

M. M. and R. S. have been partially supported for this work through NASA LTSA grant 399-20-61-00-00; R.S. has also been funded by NASA/STSCI GO grants 09101.01-A & 09102.01-A.

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Mark Claussen: National Radio Astronomy Observatory, P.O. Box 0, Socorro, NM 87801, USA (mclausse@aoc.nrao.edu).
Mark Morris: Division of Astronomy, Box 951562, UCLA, Los Angeles, CA 90095-1562, USA (morris@astro.ucla.edu).
Raghvendra Sahai: Jet Propulsion Laboratory, MS 183-900, California Institute of Technology, Pasadena, CA 91109, USA (sahai@jpl.nasa.gov).