Astrophysical Masers and their Environments
Proceedings IAU Symposium No. 242, 2007
J.M. Chapman & W.A. Baan, eds.

doi:10.1017/S1743921307013154

Maser emission in planetary nebulae

Yolanda Gómez

Centro de Radioastronomía y Astrofísica, UNAM, A.P. 3-72, C.P. 58090, México
email: y.gomez@astrosmo.unam.mx

Abstract. Stars at the top of the asymptotic giant branch (AGB) can exhibit maser emission from molecules like SiO, H_2O and OH. These masers appear in general stratified in the envelope, with the SiO masers close to the central star and the OH masers farther out in the envelope. As the star evolves to the planetary nebula (PN) phase, mass-loss stops and ionization of the envelope begins, making the masers disappear progressively. The OH masers in PNe can be present in the envelope for periods of ∼1000 years but the H_2O masers can survive only hundreds of years. Then, H_2O maser emission is not expected in PNe and its detection suggests that these objects are in a very particular moment of its evolution in the transition from AGB to PNe. We discuss the unambiguous detection of H_2O maser emission in two planetary nebulae: K 3-35 and IRAS 17347-3139. The water-vapor masers in these PNe are tracing disk-like structures around the core and in the case of K3-35 the masers were also found at the tip of its bipolar lobes. Kinematic modeling of the H_2O masers in both PNe suggest the existence of a rotating and expanding disk. Both PNe exhibit a bipolar morphology and in the particular case of K 3-35 the OH masers are highly polarized close to the core in a disk-like structure. All these observational results are consistent with the models where rotation and magnetic fields have been proposed to explain the asymmetries observed in planetary nebulae.

Keywords. Planetary Nebulae, masers, magnetic fields, individual(K 3-35, IRAS 17347-3139

1. Introduction

Planetary nebulae (PNe) represent the final stage of evolution for intermediate mass stars (1-8 $M_\odot$). A PN consists of an expanding gaseous shell of highly ionized gas that has been ejected by the star during the end of the AGB evolution, and a central star that will end as a white dwarf. The study of PN is very important not only because our Sun will end as a PN but also because these objects expel heavy elements like carbon and oxygen producing an enrichment of the interstellar medium. The lifetime of a PNe is about 10^4 years and it is expected that there are 10^4-10^5 PNe in our galaxy, from which only ∼1500 have been reported (Kohoutek 2001). PNe are characterized by exhibiting a variety of shapes (e.g. Balick & Frank 2002). Several observational studies have revealed that most of the PNe (∼75%; Manchado 2004) exhibit asymmetric morphologies that go from elliptical to very collimated outflows. One of the open questions in this field is to understand the origin of these asymmetries.

To answer this question we should review the formation process itself in the transition between the AGB and PNe stages. After completion of the H and He core burning, the star evolves to the AGB. At the top of the AGB phase, the star is surrounded by an expanding envelope of gas and dust (Caswell 1974). The study of the star in this evolutionary phase is better pursued with radio and infrared telescopes and the presence of neutral atomic and molecular gas in the envelope of the star is common (e.g Mufson, Lyon & Marionni 1975; Huggins *et al.* 1996; Josselin & Bachiller 2003; Bujarrabal 2006). For AGB stars with oxygen-rich envelopes it is possible to detect maser emission of one or more molecules, such as SiO, H_2O and OH that appear stratified in the envelope

Table 1. OH and H_2O maser emission in young PNe

PNe	OH	H_2O	Morphology	References
NGC 6302	YES	NO	bipolar	Payne *et al.* (1988)
OH 349.36-0.20	YES	NO	?	Zijlstra *et al.* (1989)
IRAS 17207-2855	YES	NO	?	Zijlstra *et al.* (1989)
PK 356+2° 1	YES	NO	?	Zijlstra *et al.* (1989)
IRAS 17347-3139	YES	YES	bipolar	de Gregorio-Monsalvo *et al.* (2004)
IRAS 17371-2747	YES	NO	?	Zijlstra *et al.* (1989)
IRAS 17375-2759	YES	NO	?	Zijlstra *et al.* (1989)
IRAS 17375-3000	YES	NO	?	Zijlstra *et al.* (1989)
OH0.9+1.3	YES	NO	?	Zijlstra *et al.* (1989)
IRAS 17443-2949	YES	YES	?	Zijlstra *et al.* (1989); Suárez *et al.* (2007)
IRAS 17580-3111	YES	YES[a]	?	Zijlstra *et al.* (1989); Suárez *et al.* (2007)
IRAS 18061-2505	NO	YES[b]	?	Suárez *et al.* (2007)
IC 4997	YES	NO	bipolar	Tamura & Kazes (1989)
K 3-35	YES	YES	bipolar	Engels *et al.* (1989); Miranda *et al.* (2001)
Vy2-2	YES	NO	shell	Davis, Seaquist & Purton (1979)
M1-92	YES	NO	bipolar	Lépine & Rieu (1974)

[a] Probably not a PN; [b] No OH maser emission (Suárez, Gómez & Morata 2007).

(e.g. Reid & Moran 1981; Elitzur 1992). As the slow and massive mass loss of the late AGB phase stops, the gravity contracts the core heating it up, and the star enters its PN phase, from this moment the maser conditions will disappear in short timescales (Lewis 1989, Gómez, Moran & Rodríguez 1990). In particular, the water molecules are expected to disappear in a timescale of decades, and only OH masers seem to persist for a considerable time ($\sim$1000 yr; Kwok 1993). In this way H_2O masers are not expected to be present in a regular PN. However, two PNe (K3-35 and IRAS 17347-3139; Miranda *et al.* 2001; de Gregorio-Monsalvo *et al.* 2004) have been found to harbor H_2O and OH maser emission, suggesting that these objects can be in an early stage of their evolution as PNe. Recently, two more PNe have been reported to exhibit H_2O maser emission and interferometric observations are required to confirm the association (Suárez, Gómez & Morata 2007). In this talk we will present details about the kinematics and polarization of the maser emission in the two confirmed PNe: K3-35 and IRAS 17347-3139.

2. Young PNe with OH and H_2O masers

Modeling of the OH maser emission in late AGB stars has shown that the typically observed double peak profile corresponds, in general, to the blueshifted and redshifted maser components which are coming mainly from the front and the back parts of the envelope, respectively (Reid *et al.* 1977). We mentioned that after the mass loss stops the OH maser can survive around $\sim 10^3$ years, then it may be possible to find OH maser emission in very young PNe. In the particular case when an ionized region is present, which is the case for young PNe, the redshifted OH maser peak component coming from the back, may not be seen because the emission is absorbed by the ionized gas, and only the blueshifted OH peak will be present (Rodríguez, Gómez & García-Barreto 1985). Then a very young PNe will have a compact ionized inner part while the outer part of the envelope remains neutral, possibly with OH maser emission. It is possible to appreciate in several young OH-PNe, with known LSR velocities, that the blueshifted OH maser components are the dominant ones (Shepherd *et al.* 1990). For example, for

https://doi.org/10.1017/S1743921307013154 Published online by Cambridge University Press

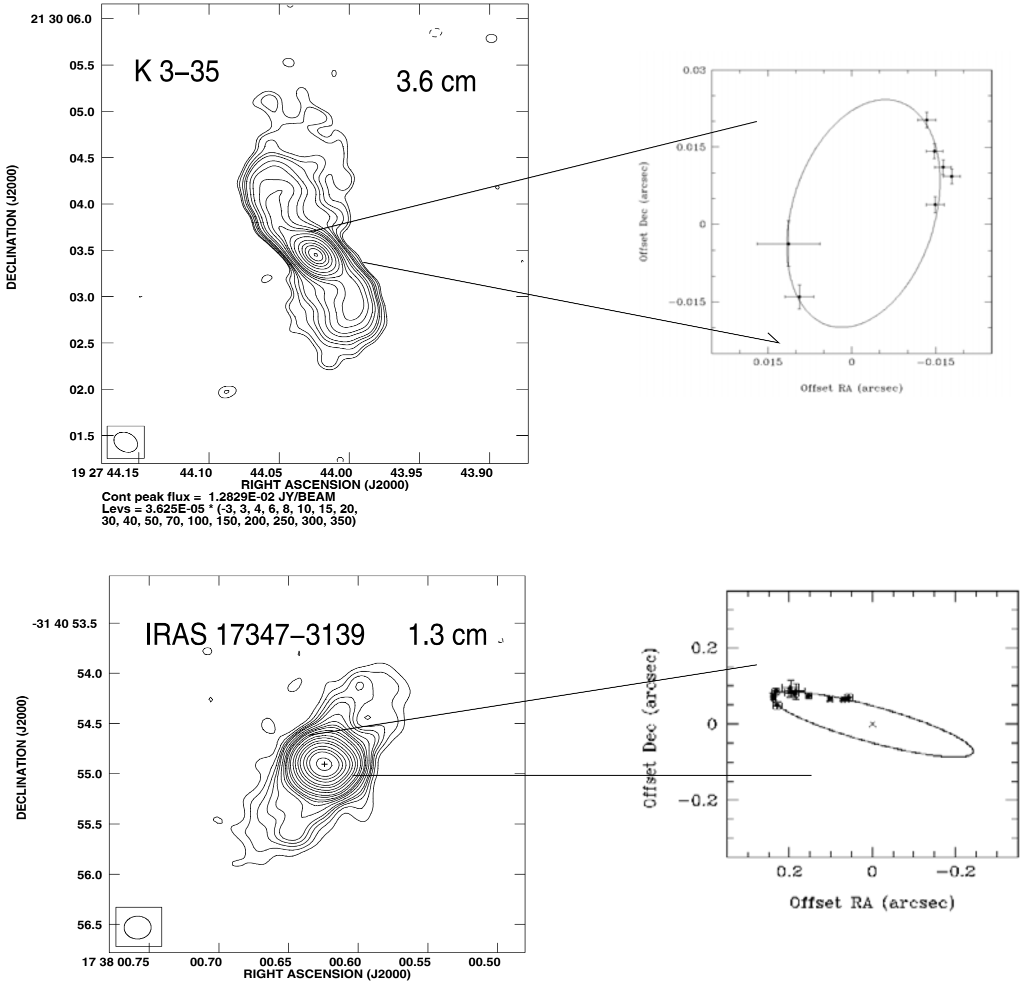

Figure 1. Left: Contour images of the radio continuum observed with the VLA in K 3-35 (Miranda *et al.* 2001) and IRAS 1737-3139 (Tafoya *et al.* 2007b). Right: The respective water maser spots with a disk fit (Uscanga *et al.* 2007).

NGC 6302 the ionized gas has a V_{LSR} (He 121α)= -29 km s^{-1} (Gómez, Rodríguez & García-Barreto 1987), while the strong OH 1612 MHz maser emission is blueshifted, arising from a velocity of -40 km s^{-1} (Payne, Phillips & Terzian 1988). Several surveys of OH maser emission have being carried out toward PNe (e.g. Johansson *et al.* 1977; Caswell *et al.* 1981; Payne, Phillips & Terzian 1988; Bowers & Knapp 1989; Zijlstra *et al.* 1989; Sevenster *et al.* 2001) showing that it is uncommon to observe OH maser emission in PNe, with the detection of very few objects (see Table 1). Then, if it is difficult to detect OH maser emission, the detection of H_2O masers in PNe is expected to be more rare, however our group have confirmed the detection of two H_2O-PNe (Miranda *et al.* 2001; de Gregorio-Monsalvo *et al.* 2004) and another two H_2O-PNe have been recently detected with the Robledo de Chavela Antenna (Suárez, Gómez & Morata 2007). In Table 1 we list the detections of H_2O maser emission in PNe.

https://doi.org/10.1017/S1743921307013154 Published online by Cambridge University Press

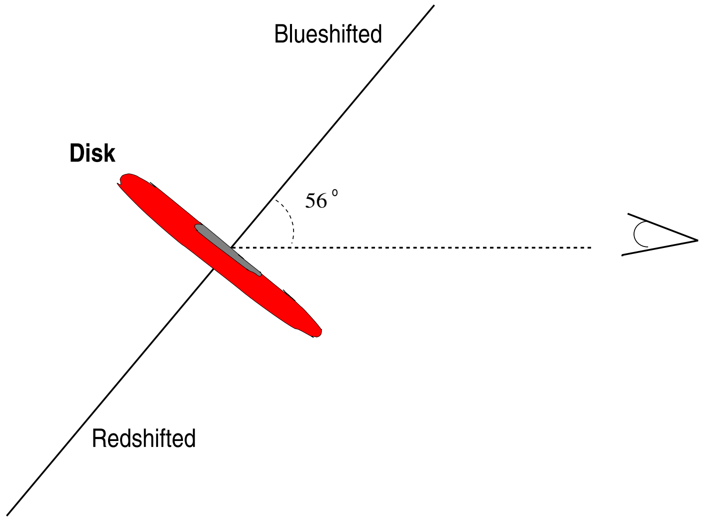

Figure 2. Schematic diagram for the inclined disk model in K 3-35.

3. K 3-35 and IRAS 17347-3139

The first confirmed cases of PNe where H_2O maser emission is present and coexistent with OH maser and radio continuum emission are: K 3-35 (Miranda *et al.* 2001) and IRAS 17347-3139 (de Gregorio-Monsalvo *et al.* 2004). Both H_2O-PNe are emission line nebulae that exhibit bipolar morphologies at radio wavelengths (K 3-35: Aaquist 1993; Miranda *et al.* 2001, IRAS 17347: Tafoya *et al.* 2007b) and the H_2O masers are arising from the core of the sources in a torus-like structure (see figure 1). In the particular case of K 3-35, there is also H_2O maser emission arising from the tips of the bipolar lobes at 5000 AU from the central star (Miranda *et al.* 2001; Gómez *et al.* 2003). Bipolar morphologies in these H_2O-PNe are also appreciated from optical/IR images (Sánchez-Contreras *et al.* 2006). The systemic LSR velocities for these two H_2O-PNe, obtained from CO observations, are 24±3 km s^{-1} for K 3-35 (Tafoya *et al.* 2007a) and −55 km s^{-1} for IRAS 17347-3139 (Uscanga *et al.* 2007). The LSR velocities of the H_2O maser components in these PNe appear blueshifted, <24 km s^{-1} for K 3-35 (Miranda *et al.* 2001; Gómez *et al.* 2003; Tafoya *et al.* 2007a) and $\geqslant -65$ km s^{-1} for IRAS 17347-3139 (de Gregorio-Monsalvo *et al.* 2004; Uscanga *et al.* 2007). In general, young PNe have a very high molecular to ionized gas mass ratio (Huggins *et al.* 1996; Josselin & Bachiller 2003). In the case of K 3-35, the ratio of molecular to ionized mass is ∼2 and the recent detection of HCO^+ emission suggests the presence of very high density molecular gas (∼10^5 cm^{-3}) that could be protecting the H_2O molecules from the dissociating radiation of the central star (Tafoya *et al.* 2007a). The bipolar morphology, and the presence of large amounts of neutral molecular gas not only suggest that these objects are young, but also that they have followed a similar evolutionary track corresponding to massive progenitors.

4. Kinematics of the H_2O masers

Figure 1 shows radio continuum contour images and the H_2O maser spot positions for K 3-35 and IRAS 17347-3139. Modeling of the H_2O masers was made for a homogeneous disk-like structure fitting each maser spot velocity with an expanding and rotating disk.

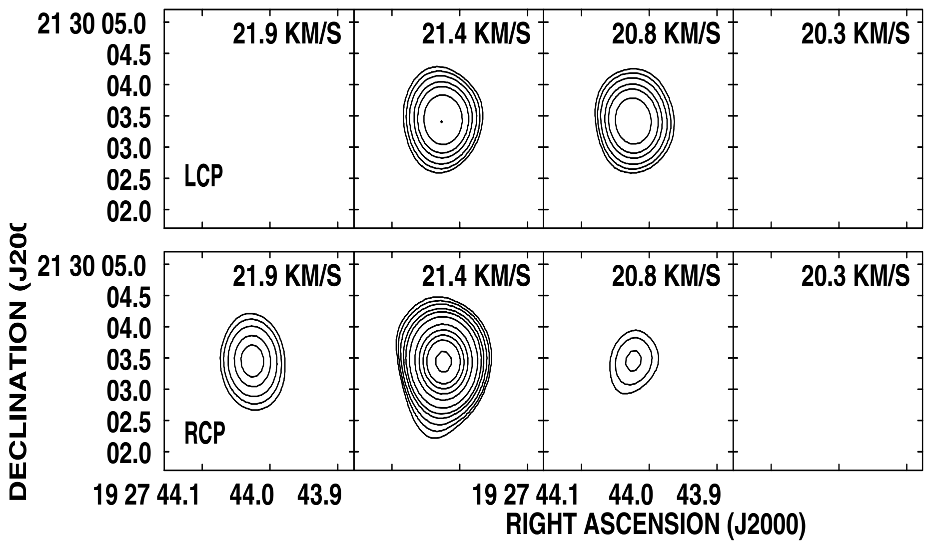

Figure 3. Contour images of OH 1720 MHz emission from K 3-35. Top panels are for the left circular plarization (LCP) and the bottom panels are for the right circular polarization (RCP) maser emission. The LSR velocities are indicated in the top right-hand corner of each image. Contours are 5, 7, 10, 15, 20, 30, 50, 70, 90, 110 and 150 times 8 and 9 mJy beam^{-1}, the *rms* noise of the LCP and RCP images, respectively.

For K 3-35 the model resulted in expanding and rotating velocity values of 1.1 km s^{-1} and 3.6 km s^{-1}, respectively. The inclination angle of the disk, between the line-of-sight and the major axis of the outflow, was also derived (56°) (see figure 2), which is in agreement with having the north lobe of the outflow blueshifted and the south redshifted. The estimated radius of the ring is $0\rlap{.}''023$ (∼ 100 AU). For IRAS 17347-3139 it was more difficult to do the modeling since the H_2O masers are interpreted as tracing only one edge of the equatorial disk. However, in both cases the orientation of the major axis of the rings appears perpendicular to the corresponding outflows, supporting a disk model interpretation (Uscanga *et al.* 2007).

5. Equatorial magnetic field in K 3-35

The detection of magnetic fields in PNe is a key parameter to understand the generation of jets and bipolar structures in PNe (see Vlemmings; these proceedings). K 3-35 is one of the few PNe where magnetic fields have been detected (Gómez *et al.* 2005). In particular, the OH 1665 MHz maser emission toward K 3-35, was found to be very highly polarized (>50%), suggesting the presence of a magnetic field (Miranda *et al.* 2001). Since the 1665 MHz maser spots seems to be tracing an elongated structure perpendicular to the bipolar outflow, it was proposed that they could be tracing an equatorial magnetic field. New VLA observations of the four OH maser transitions confirmed the strong circular polarization of the OH 1665 MHz emission and assuming that at least one Zeeman pair is present, we derived a magnetic field in the line-of-sight of 0.14 mG at a radius of 250 AU. In addition, the OH 1720 MHz transition was clearly detected. A single OH 1720 MHz feature was previously reported by te Lintel Hekkert (1991) toward K 3-35. Our VLA OH observations confirmed the presence of a single feature in the spectrum of the 1720 MHz and also proved that it is associated with the H_2O-PNe, since the peak position of the maser feature coincides with the peak of the radio continuum emission (Gómez *et al.* 2005). It is the only one PNe where the OH 1720 MHz maser transition has been detected. A contour image of the OH 1720 MHz from K 3-35 in its left and right circular polarizations is shown in figure 4. Assuming that a Zeeman pair is present, a magnetic field of 0.8 mG was derived at a radius of 120 AU. The strength of the magnetic field in K 3-35 is in agreement with the values derived toward evolved stars.

6. Conclusions

The presence of H_2O and OH maser emission in PNe is not common, and their detection suggest that these objects are in a very early phase of their evolution. In particular the presence of H_2O maser emission has been confirmed only in two PNe (K 3-35 and IRAS 17347-3139), and from a recent H_2O survey, made with the Robledo de Chavela Antenna, two more PNe seem to be detected. The H_2O maser positions in K 3-35 and IRAS 17347-3139 show kinematics consistent with masers located in rings. From modeling, it is derived that in K 3-35 there is a rotating and expanding disk perpendicular to the bipolar outflow. There is evidence of magnetic fields in K 3-35 that could help to constrain the models for jets and bipolar morphologies in PNe.

Acknowledgements

YG acknowledge financial support from PAPIIT-UNAM (IN100407) and CONACyT, México.

References

Aaquist, O. B. 1993 *A&A* 267 260
Balick, B. & Frank, A. 2002 *ARA&A* 40, 439
Bujarrabal, V. 2006 *Planetary Nebulae in our Galaxy, IAU Proceedings* 234, 193
Bowers, P. F. & Knapp, G. R. 1989 *ApJ* 347, 325
Caswell, J. L. 1974, *IAU Proceedings. Ed: F. J. Kerr and S. C. Simonson* 60, 423
Caswell, J. L., Haynes, R. F., Goss, W. M., & Mebold, U. 1981 *AuJPh* 34, 333
Davis, L. E., Seaquist, E. R., & Purton, C. R 1979, *ApJ* 230, 434
de Gregorio-Monsalvo, I., Gómez, Y., Anglada, G., Cesaroni, R., Miranda, L. F., Gómez, J. F., & Torrelles, J. M. 2004, *ApJ* 601, 921
Elitzur, M. 1992, *ARA&A* 30, 75
Gómez, Y., Miranda, L. F., Anglada, G. & Torrelles, J. M. 2003, *Planetary Nebulae, IAU Proceedings* 209, 263
Gómez, Y., Moran , J. M., & Rodríguez, L. F. 1990, *RevMexAA* 20, 55
Gómez, Y., Rodríguez, L. F., & García-Barreto, J. A. 1987, *RevMexAA* 14, 560
Gómez, Y., Tafoya, D., Anglada, G., *et al.* 2005 *Memorie della Societa Astronomica Italiana* 76, 472
Huggins, P. J., Bachiller, R., Cox, P. & Forrveille, T. 1996, *A&A* 315, 284
Johansson, L. E. B., Andersson, C., Goss, W. M., & Winnberg, A. 1977, *A&AS* 28 199
Josselin, E. & Bachiller, R. 2003, *A&A* 397, 659
Kohoutek, L. 2001, *A&A* 378, 843
Kwok, S. 1993, *ARA&A* 31, 63
Lépine, J. R. D. & Rieu, N. Q. 1974, *A&A* 36, 469
Lewis, B. M. 1989, *ApJ* 33, 234
Manchado, A. 2004, *ASP Conference Proceedings* 313, 3
Miranda, L. F., Gómez, Y., Anglada, G. & Torrelles, J. M. 2001, *Nature* 414, 284
Mufson, S. L., Lyon, J., Marionni, P. A. 1975, *ApJ* (Letters) 201, L85
Payne, H. E., Phillips, J. A., & Terzian, Y. 1988 *ApJ* 326, 368

https://doi.org/10.1017/S1743921307013154 Published online by Cambridge University Press

Reid, M. J., Muhleman, D. O., Moran, J. M., Johnston, K. J., & Schwartz, P. 1977, *ApJ* 214, 60

Reid, M. J. & Moran, J. M. 1981, *ARA&A* 19, 231

Rodríguez, L. F., Gómez, Y. & García-Barreto, J. A. 1985, *RevMexAA* 11, 139

Sánchez-Contreras, C., Le Mignant, D., Sahai, R., Chaffee, F. H., & Morrism M. 2006, *Planetary Nebulae in our Galaxy, IAU Proceedings* 234, 71

Sevenster, M. N., van Langevelde, H. J., Moody, R. A., Chapman, J. M., Habing, H. J., & Killeen, N. E. B. 2001, *A&A* 366, 481

Shepherd, M. C., Cohen, R. J., Gaylard, M. J., & West, M. E. 1990 *Nature* 344, 6266

Suárez, O., Gómez, J. F., & Morata, O. 2007, *A&A* in press

Tafoya, D., Gómez, Y., Anglada, G. *et al.* 2007a, *AJ* 133, 364

Tafoya, D., *et al.* 2007b, *in preparation*

Tamura, S. & Kazes, I. 1989 *Planetary Nebulae, IAU Proceedings* 131, 209

te Lintel Hekkert, P. 1991 *A&A* 248, 209

Uscanga, L. *et al.* 2007 *in preparation*

Zijlstra, A. A. *et al.* 1989, *A&A* 217, 157