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Memorie della

Francesco and masers

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Abstract. Masers in general are signposts of interesting astronomical sources and phenomena. In particular, they are found in the immediate environment of young stellar objects. Abundant observational evidence suggests that H_2O masers arise in the outflows from such sources in their earliest evolutionary phases and are in fact powered by accretion. As such they are intimately connected with the core of Francesco Palla's science. And indeed, H_2O masers were at the start and an essential component of a highly successful research program initiated by Francesco, the identification and characterization of a significant sample of massive young stellar objects. An overview is given of the sustained H_2O maser research program conducted over many years with the Medicina 32-meter radio telescope, in which Francesco played a vital part. Last, but not least, with Steven Stahler, Francesco co-authored an excellent chapter on interstellar masers that formed a part of *The Formation of Stars*, their classic textbook of the field.

Key words. Interstellar medium: astrophysical masers – Stars: Protostars

1. Introduction

In star-forming regions, interstellar maser emission is mainly observed from three molecular species: hydroxyl (OH), water (H_2O) and methanol (CH_3OH) (see, e.g., Gray 2012). All of these are found in the close vicinity of young stellar objects (YSOs). While OH and CH_3OH masers are exclusively associated with high-mass YSOs, H_2O masers have been found toward numerous low- *and* high-mass YSOs, predominantly in the strongest transition, the $J_{K_a,K_c} = 6_{16} - 5_{23}$ rotational line that has a frequency near 22.2 GHz in the so-called K-band of the radio frequency range. The upper energy level of this line is at an elevated energy corresponding to 643 K above the ground state of ortho-H_2O. This, together with the large velocity ranges covered by their spectral features, of tens and even up to > 100 kms^{-1} and the large proper motions measured by Very Long Baseline Interferometry, VLBI (see, e.g. Zhang et al. 2013), indicates that H_2O masers are produced in the fast interstellar shocks of outflows from very young stellar objects (Hollenbach et al. 2013). Given this, naturally H_2O masers resided near the center of Francesco's research.

2. Maser research at Medicina

In 1983, a 32-meter diameter paraboloid radio telescope was built at the Medicina Radio Astronomical Station operated by the Istituto di Radioastronomia-CNR, Bologna, Italy. As an important element of the European VLBI Network (EVN), it has mainly been used for astrometric and geodesic studies, but also for milli-arcsecond resolution studies of active galactic nuclei and maser sources. However, quite early on, in addition, Marcello Felli's group at the Osservatorio Astrofisico di Arcetri initiated an observing program that used this antenna as a *single dish telescope*. This program, presented in §3, consisted of extensive observations of the 22.2 GHz H_2O maser line and, after being started in 1987, it would would run for more than two decades.

2.1. Enter Francesco

Apart from being a member of the large Arcetri H_2O maser team, Francesco's own first foray into H_2O maser observations resulted in a Research Note published in *Astronomy & Astrophysics*. It was co-authored with Carlo Giovanardi and reported maser searches in the molecular cloud in Serpens associated with the Sharpless 68 emission nebula (Palla & Giovanardi 1989). The results were rather inconspicuous, since no new masers could be found, despite a total of six observing runs at Medicina during 1987/1988. Only during one of these sessions a previously known maser source with a single narrow emission feature could be detected at a radial velocity consistent with that published earlier. As the first sentence of the paper's Introduction puts it: "Water vapor masers in the Serpens cloud are sneaky objects."

Subsequent Medicina H_2O maser searches toward a large sample of low-mass YSOs also had a quite low detection rate, which is consistent with the meagre outcome of the Serpens campaign (Persi et al. 1994). An interesting possibility is that H_2O maser variability is correlated with the rather rare FU Ori-type episodic accretion events. This could be examined by temporally closely spaced (and thus quite expensive) simultaneous monitoring of the H_2O line and optical/infrared emission (see §3.2).

3. Diverse H_2O maser research at Medicina

3.1. The Arcetri H_2O maser catalog

The first two papers on the Arcetri H_2O maser observing program presented a census of known masers and marked the start of a large-scale program of H_2O maser observations with the Medicina telescope. The first article reported new observations of all known interstellar and stellar H_2O masers above a declination of $-30°$. It formed the basis of a continuous single dish observing campaign of such sources (Cesaroni et al. 1988). That paper gave a list of detected sources with basic information (peak flux densities, radial velocities) and statistics, while a following article presented the results of all the measurements made with the Medicina 32-m antenna (including flux density upper limits for non-detections) plus representative spectra of all the 203 (out of 509) detected sources (Comoretto et al. 1990). After the maser team member Jan Brand took a position at the Istituto di Radioastronomia (then CNR, now INAF) in Bologna, he established maser research at his new institute and continued to be a very prominent member of the team. These first two papers introduced what became to be known as the "Arcetri catalog", which went through several updates (Brand et al. 1994; Valdettaro et al. 2001) and spawned a number of interesting, even theoretical studies (see, e.g., Cesaroni 1990). The catalog itself has high legacy value. For example, it provided targets for trigonometric parallax measurements of maser sources with the Very Long Baseline Array (VLBA) in the framework of the Bar and Spiral Structure Legacy Survey (BeSSeL) that have provided direct distance and three-dimensional velocity determinations for high-mass star-forming regions throughout the Galaxy (Reid et al. 2014). The radial velocities listed in the Arcetri catalog were used for kinematic distance determinations, obtained by matching the measured velocities with a model of Galactic rotation (Reid et al. 2016).

In addition to the catalog and monitoring effort (see below), special interest was dedicated by the Arcetri/Bologna team to H_2O maser searches toward selected classes of star-forming regions. Francesco was a coauthor of most of the Medicina/H_2O maser articles, some more of which will be discussed in the next sections.

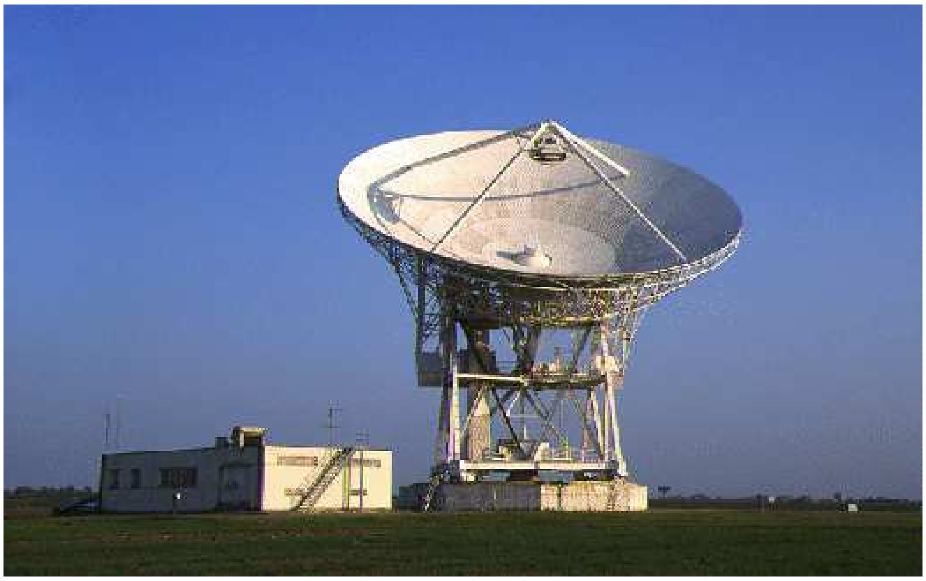

Fig. 1. The 32-meter diameter telescope of the Istituto Nazionale di Astrofisica (INAF). It is located near Medicina, close to the Adriatic Sea. Picture taken from the 2009 International VLBI Service for Geodesy and Astrometry (IVS) Annual Report by Orfei et al. (http://ivs.nict.go.jp/mirror/publications/ar2009/nsmedi/)

3.2. The Arcetri H_2O monitoring program

Another major long-term H_2O maser program conducted at Arcetri consisted of monitoring the 22.2 GHz H_2O line for a sample of 43 star-forming regions with a large range in luminosity and 22 evolved stars for about 20 years at a sampling rate of 4–5 observations per year, (Valdettaro et al. 2002; Brand et al. 2003, 2007; Felli et al. 2007).

Very recently, such maser monitoring has received substantial attention since a dramatic (simultaneous) increase in the flux densities of the 22.2 GHz H_2O and the 6.7 GHz CH_3OH maser lines appears to be connected with a very strong increase in the submillimeter dust emission flux of an embedded massive YSO (MYSO) in the NGC 6334 I region (Hunter et al. 2017). Similarly, an outburst in the 6.7 GHz CH_3OH maser line triggered a near- and far-infrared wavelength campaign than revealed that it was accompanied (or followed) by an increase of the bolometric luminosity of an MYSO in the Sharpless 255 region by about an order of magnitude (see Caratti o Garatti et al. 2017, and Alessio C. o G.'s contribution to these proceedings). It is a distinct possibility that these events are the results of episodic accretion on MYSOs, i.e., the high mass equivalent of the FU Ori phenomenon; see § 2.1. Thus maser monitoring has a huge potential of triggering multi-wavelength studies that can offer exciting new and unexpected views on the formation of high-mass stars. However, they would have to be conducted with a higher frequency than the several months per year interval of the Medicina H_2O maser monitoring program, which may serve as a precursor to such efforts.

3.3. Other Arcetri H_2O maser science

In addition to their H_2O maser surveys of high mass star forming regions, Francesco and his collaborators conducted several maser search campaigns toward different classes of other targets. Several studies addressed the star formation potential of bright-rimmed clouds, objects illuminated by radiation from the outside. The relatively modest maser detection yield was used to argue that most such objects host young stellar objects of low luminosity, likely in an evolutionary phase later than the protostellar Class 0 sources (with which H_2O masers are predominantly associated) and that low-mass star formation is the most natural outcome of the external compression induced by the ionization front from nearby massive stars (Valdettaro et al. 2005, 2007).

4. H_2O in masers in high-mass star-forming regions

In a highly influential article based on measurements with the Infrared Astronomical Satellite (IRAS), Wood & Churchwell (1989) plotted the measured $\log[60\mu m/12\mu m]$ versus $\log[25\mu m/12\mu m]$ flux ratios, i.e., the [60 – 12] vs. the [25 – 12] colors, of sources in the IRAS Point Source Catalog (PSC[1]).They found that objects that could be identified as ultra-compact HII regions (UCHIIRs) occupied a distinct region in the resulting diagram. This spurred a large number of studies that yielded increasing samples of dust-embedded MYSOs. The identified objects included a number of *genuine* UCHIIRs, i.e., sources with radio wavelength free-free emission that could be detected with the Very Large Array (VLA). However, many of the sources turned out to be without easily detectable radio emission, i.e., precursors of UCHIIRs.

Palla et al. (1991) defined a sample of 260 sources for an H_2O maser search with the Medicina antenna. In a modified version of the Wood & Churchwell flux ratio diagram, these objects satisfied the ranges of $60/25\mu m$ and $100/60\mu m$ flux ratios proposed by Richards et al. (1987), who conducted a search for the high critical density tracer HCO^+ targeted at star-forming gas. In particular, sources were required to have "no positional coincidence with known HII regions". This rejected extended, well-developed HII regions with strong radio flux and selected sources in early evolutionary stages, i.e. the UCHIIR phase and younger. A total of 125 of the 260 sources occupy the same area as the "UCHIIRs" in the Wood & Churchwell $60/12\mu m$ vs. $25/12\mu m$ flux ratio diagram. Of these, 26% have H_2O maser detections, whereas the 135 remaining sources are found in to the lower left of the UCHIIRs in that diagram. Only toward 9% of the sources in this second sub-sample H_2O maser emission was found. A subsequent study with an extended sample confirmed the existence of a sharp cutoff in H_2O detections with low 25/12 μm flux ratios (Palla et al. 1993).

Palla et al. (1991) concluded that sources in the first group are more developed than those belonging to the second one. Reflecting their location in the IRAS flux density ratio diagram, the first and second group of sources were termed "high" and "low". This work was a starting point for Sergio Molinari's Bologna dissertation, the main parts of which were published in a series of influential papers. The first of these used NH_3 observations to flesh out the differences of the two classes of sources (Molinari et al. 1996). Two other major articles discussed high resolution VLA radio continuum imaging and the samples' dust properties (Molinari et al. 1998, 2000). These papers have Jan Brand (Sergio's advisor in Bologna) and Arcetri's Francesco and Riccardo Cesaroni as co-authors. They were followed by a series of articles concentrating on particularly interesting objects of the sample.

5. Chapter 14 of "The Book"

In 2004 I was approached by Steve Stahler and also the Wiley-VCH Verlag with the request to review a chapter on interstellar masers that was to be part of a book they had under production: *The Formation of Stars* by Steven W. Stahler and Francesco Palla. This now famous tome was destined to become a classic text book on its subject. I was very impressed with this text, which I told the publisher. It became chapter 14 of the final book (Stahler & Palla 2005) and starts with a clear summary of the observa-

[1] The IRAS PSC lists ~ 250000 compact infrared point sources observed by IRAS in the course of its all-sky survey at 12, 25, 60, and 100 μm; see https://heasarc.gsfc.nasa.gov/ W3Browse/iras/iraspsc.html

tional characteristics of masers in star forming regions that is followed by a rigorous, but succinct treatment of maser theory, a highly complex topic, and the pumping of H_2O and OH masers. Following this, masers tracing jets and outflows are discussed, augmenting the exposition of these topics in the book's preceding chapter. Finally, masers in the famous Orion-KL regions are addressed. Like this whole superb book, its maser chapter impressively documents the combination of deep theoretical insight and a profound and comprehensive understanding of the very diverse observational aspects of its field of research. It was written by two of the premier researchers in the field who represented a winning combination of a pure theoretician and a theoretician with a strong observational bend.

6. Conclusions

Like many other astronomers, Francesco Palla was fascinated by the rich picture presented by cosmic masers. He employed these intriguing sources as tools to investigate the "larger picture" of their context, the formation of stars.

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