The super-resolved megamasers of NGC 4258
Impellizzeri, C.M.V.

GALAXIES

The super-resolved megamasers of NGC 4258

The precise location of megamaser emission regions in galactic accretion disks has been challenging to pinpoint. Now with interferometric observations leveraging baselines larger than the Earth's diameter, the missing information is getting closer and closer.

C. M. Violette Impellizzeri

Writing in *Nature Astronomy*, Willem Baan and colleagues[1] present space-based observations of the megamasers in galaxy NGC 4258 taken with interferometric baselines that span from Earth to space, achieved by the Space Radio Telescope of the RadioAstron Observatory. Three different sets of observations are presented in the paper, with increasing maximum baselines of 1.3, 9.5 and 19.5 Earth diameters, and reaching maximum angular resolutions of 11–23 microarcseconds. This provides 40–90 times better resolution than previous ground-based Very Long Baseline interferometry (VLBI) observations. With this super-resolution, Baan and colleagues show how the megamaser spectra change with the longer Earth–space baselines, revealing a pattern with velocity peaks that are spaced at regular intervals. As the megamasers are known to originate in the black hole accretion disk of NGC 4258, the authors explain the evenly spaced peaks as the result of periodic magnetorotational instabilities (MRI) inside the disk. These shear-driven instabilities are expected to grow into radial wave patterns, ultimately producing a series of 'fingers' of high and low angular momentum.

Although the theory is not new, it has been challenging to test, owing to the small angular scales involved. The new observations lend credible support to the theory of MRI-driven accretion: it not only explains the observed periodicity in Doppler velocity but could more broadly also explain the origin of the mass accretion in disks around black holes, the existence of over-densities and finally maser variability itself. The confirmation of the prediction that the scale height should match the size of the masing cells is also a positive self-consistency check. The maser community has been eagerly awaiting these space-VLBI results for years, and so it is a great pleasure to finally see them. These observations offer the highest angular resolution of any megamaser accretion disk yet observed. Although imaging is not yet possible owing to the (still) limited number of baselines, the observations manage to address important questions, the most essential being: can water megamasers be detected at microarcsecond (or au) resolution? Baan et al. show that the answer to this question is yes. They also begin to tackle more fundamental questions. For example, what is the intrinsic size of maser cells? Can we resolve them? Do masers arise in a clumpy medium? What causes velocity coherence? What causes the variability? Why do some accretion disks have megamaser emissions and others not?

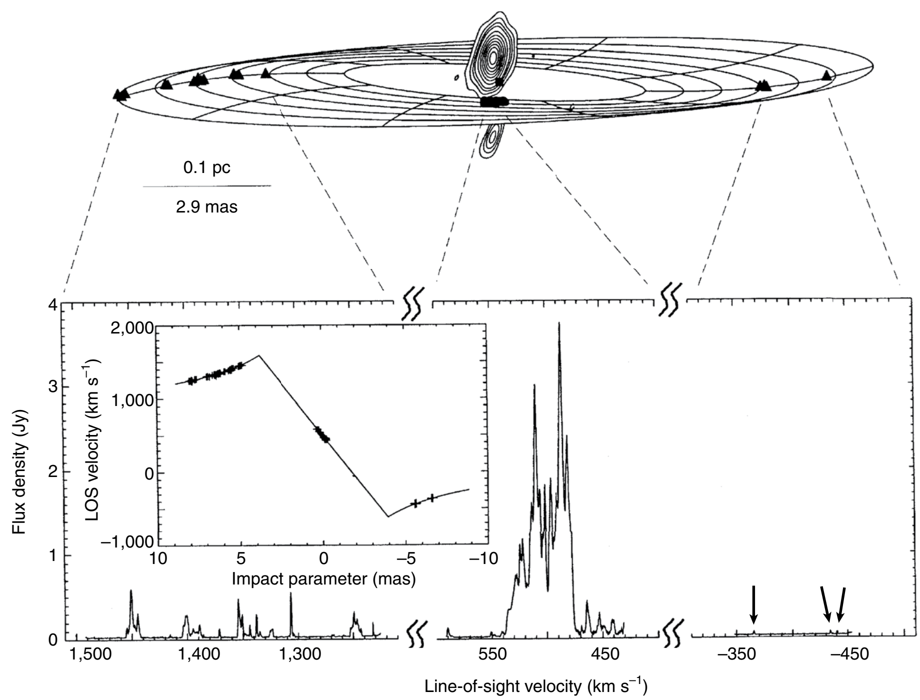

Fig. 1 | The megamasers in the disk of NGC 4258 seen on VLBI scales. These radio observations from the late 1990s achieved milliarcsecond-level angular resolution. Baan et al.[1] leveraged the power of space-VLBI to reach microarcsecond-level resolution for the same target. LOS, line of sight. Reproduced with permission from ref. [14].

Megamaser is the term commonly used to describe masers originating from other galaxies. They are referred to as 'mega' because they are (typically) intrinsically a million times more luminous than their counterparts within our Galaxy[2]. However, this does not mean that they are bright; owing to their distances, they tend to be relatively weak in most galaxies (typically a few tens to a few hundreds of millijanskys). On the other hand, due to their compact nature and extreme brightness temperatures ($T > 10^{17}$ K), megamasers can still be studied with VLBI at milliarcsecond (mas) resolutions. These high-resolution VLBI observations have yielded spectacular results in the past 20 years of research, obtained in nearby and in high-redshift galaxies (for examples, see refs. [3,4]).

Water megamasers are particularly exciting to study at mas resolution, because they originate from gas that is extremely close — within a few light-years — to supermassive black holes. VLBI studies of these water megamasers reveal exquisite details of thin, warped disks and outflows at distances of typically 0.1–0.9 pc; this is the closest look ever obtained into molecular gas surrounding black holes. Water megamasers have therefore been pivotal in revealing structures, inclinations and orientations of the molecular accretion disk. Because the masers trace gas orbits at high resolution, they provide the most accurate measurements of black hole masses in astronomy (for instance, ref. [5]), a vital measurement for studying the coevolution of supermassive black holes and galaxies[6] in the lower-mass regime (for example, ref. [7]). Another important development of megamaser studies has been to derive geometric distances to the galaxies in the Hubble flow, to obtain an independent measurement of the Hubble constant, constraining cosmological models[8]. Megamaser disk studies in the past have also been used to rule out extremely dense star clusters in the centres of active galaxies by setting limits to the central density[5].

There are about 180 water megamaser galaxies known so far, and only about 15 are known to reside in maser accretion disks. Of those, NGC 4258 has by far the best-studied disk, with observations revealing striking disk details and peculiarities. This is one of the reasons that NGC 4258 was such a great choice for this space-VLBI experiment. Being the closest galaxy (7.6 Mpc) in the Northern Hemisphere known to host water masers also translates into bright maser emission (with peaks of ~3–4 Jy) spread over a relatively large angular scale in the sky, thus meaning that it can be mapped in even more detail (see Fig. 1). NGC 4258 was also the first megamaser galaxy to be discovered and to be associated with the supermassive black hole at the centre[9]; it remains an archetype for all maser studies. This discovery established early on that water masers are emitted from the very central, inner-parsec region and that they can trace a thin, warped disk, revealing acceleration in the 'systemic' masers (as is also described in the paper by Baan et al.). More recently, the masers in NGC 4258 have been used to 'anchor' the Cepheid distance–luminosity relation to derive an ever-more-accurate measurement of the Hubble constant[10]. But despite some of these successes and the high scientific impact of maser studies to study black hole accretion, fundamental questions have remained for decades, and include uncertainties on maser excitation mechanisms, population inversion and basic conditions in the disks; it is a limitation in the field that most models used today still trace back to the 1990s (for example, ref. [11]).

Baan and collaborators have created a new milestone for the megamaser community. Because it shows that the masers can be detected (and are not yet resolved) at scales of 84–861 au, as well as uncovering those velocity patterns in the spectra, this is a result worth paying attention to. Whether the MRI scenario is at play or not, it should be taken seriously, and should be tested on more disks and different systems.

What will the future bring? These first space-VLBI observations may provide an important step towards reviving this exciting field. I particularly look forward to one day seeing the first space-VLBI maps of megamaser disks at microarcsecond resolutions and, eventually, observations of even more water-maser transitions to better understand disk excitation, dynamics and accretion. This is also becoming possible with spectral-line millimetre-VLBI observations on the horizon and the ongoing explorations of submillimetre water-maser transitions, thanks to sensitive submillimetre telescopes (for example, refs. [12,13]). But today certainly opens a new chapter for these studies, as Baan et al. demonstrate the power of space-VLBI and the potential for future space-based radio- and millimetre-wave observatories for the coming decade. ❐

C. M. Violette Impellizzeri ✉
Leiden Observatory, Leiden, the Netherlands.
✉*e-mail: violette@strw.leidenuniv.nl*

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Competing interests

The author declares no competing interests.