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A large-scale OH maser filament in W3(OH)

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Abstract. Phase-referenced MERLIN spectral line observations have been made of the OH-HII region W3(OH) as part of a larger survey of excited OH 4.7-GHz masers. We observed the three bright excited OH 4765-MHz maser spots that are well-documented in the literature. Using a larger (100 mas) beam to observe more extended emission we discovered a long maser filament extending 1.0 arcsec North-South between two of the spots. We also resolved an extended core-halo structure for the maser spots. The OH filament corresponds with arcs of OH ground-state maser spots and with absorption features of highly excited OH. It has a brightness temperature of $\sim 4 \times 10^5$ K and a North-South velocity gradient. We suggest that the filament traces a large-scale (~2200 AU) shock.

1. Introduction

OH masers are frequently used to probe the physical conditions in compact HII regions at high resolution. OH masers are ideal target sources because they are bright, compact, and most of all highly abundant in regions of massive star-formation. Their velocities and proper motions can be used to trace gas kinematics and observations of their polarisation properties allow us to investigate the local magnetic field structure.

Since the first discovery of masing OH gas was made in the region by Weaver et al. (1965), W3(OH) has been the most intensely studied OH-HII region in the Galaxy. What makes W3(OH) so interesting is that it contains emission and/or absorption from every OH transition ever observed extraterrestrially, from 1.6-GHz ground state transitons to the highly excited 23-GHz lines. It also contains bright H_2O and CH_3OH masers, allowing us to undertake not only mulifrequency comparisons of OH maser positions but also to determine the conditions required to produce masers in different chemical species.

Over the years, maser pumping models have been developed for muliple frequencies of OH propagating through a single column of gas. These predict that certain pairs or groups of OH masing frequencies are able to co-exist under the same physical conditions. As Doel et al. (1990) noted, observing masers at several frequencies can help to reduce the number of possible interpretations of the conditions within such a region. One of the most common associations occurs between excited OH 4765-MHz and ground-state 1720-MHz masers and this was sucessfully modelled by Gray, Doel & Field (1991). Rigorous testing of such models requires confidence that OH masers are truly associated however, which in turn requires high resolution interferometric observations with phase-referencing to allow absolute positions to be determined accurately.

Baudry et al. (1988) were the first to observe excited OH masers at 4765 MHz in W3(OH) using VLBI. They observed three spots, called A, B and C at –43.24, –43.46 and –45.01 km^{-1} respectively. Gardner et al. (1983) had previously observed two of these spots (A and C) using the VLA and an additional component between spots A and B at –44.3 km^{-1}. It was suggested by Baudry et al. that this failure to observe spot B may have been due to the inability of the VLA to separate the two components, which had very similar velocities, with a 1.3-arcsec synthesised beam. The three spots were subsequently observed at the same positions and velocities by Gray et al. (2001) using MERLIN and by Palmer, Goss & Devine (2003) using the VLBA. At VLBA resolution spot B is found to be elongated ~ 14 mas NW-SE while spot C separates into three elongated components spread approximately North-South over 30 mas. In the same paper, Palmer et. al. also presented monitoring observations of W3(OH) using the VLA. They noted that the VLBA only observed 30% of the total 4765 MHz line flux found by the VLA, and also that the "plateau" of emission between the two VLA spectral peaks was completely resolved out by the VLBA. Using MERLIN we have found this "missing" emission.

2. Observations and data reduction

Phase-referenced observations of W3(OH) were made on 15th March 1995 using the Mark II telescope at Jodrell Bank and MERLIN[1] outstation telescopes at Cambridge, Darnhall, Defford, Knockin and Pickmere. The longest MERLIN baseline was Knockin-Cambridge (218 km), giving a 60 mas minimum fringe spacing. The 27-hour observing run was frequency-switched between 4765, 4750 and 4660 MHz and observations were made in left-hand circular (LHC) and right-hand circular (RHC) polarisations. The observation schedule consisted of 3 × 3 minutes on the phase-calibrator source (0224+671), interspersed with 2 × 5 minutes 30 seconds on source. This process was then repeated cyclically through the 3 frequencies.

Initial editing was carried out to remove any 'bad' data points caused by interference and instrumental effects using the Jodrell Bank d-programmes. Here a gain-elevation correction was also applied, to account for the different effects of atmospheric absorption and ground radiation at low elevation. The mean flux was calculated for each polarisation over the shortest

[1] MERLIN is a national facility operated by the University of Manchester at Jodrell Bank Observatory on behalf of PPARC.

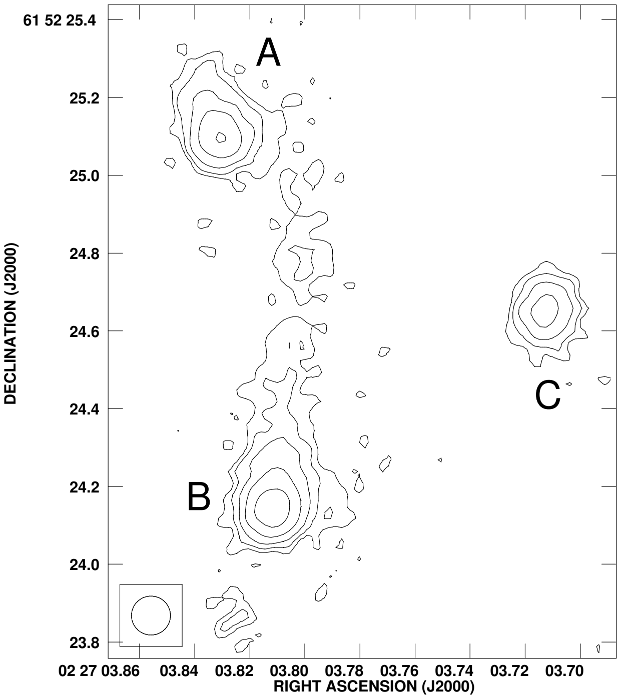

Fig. 1. Contour map of the OH 4765-MHz maser emission in W3(OH), integrated over the velocity range –43.5 to –44.8 km s^{-1}. The OH filament stretches between spots A and B. The Half-Power Beam Width (100 mas) is shown at the lower left of the panel. Contour levels are 6.18 × (1, 2, 4, 8, 16, 32) mJy beam^{-1}.

baseline and the fluxes were calibrated, using estimated fluxes for 3C286 of 7.296, 7.310 and 7.398 Jy at 4765, 4750 and 4660 MHz respectively. Amplitude, phase and bandpass calibration were carried out in the Astronomical Image Processing System (AIPS) and the full data cubes were mapped in *I*-Stokes. Maser spots were defined as features occurring in no less than 3 adjacent frequency channels with a phase-centre shift <∼2 pixels (∼30 mas). The positions and intensities of OH maser spots were determined by fitting two-dimensional Gaussian components to the individual components in each spectral channel where the feature was evident using the AIPS task JMFIT. The weighted mean positions and velocities were then calculated using Equation (1)

$$x = \frac{\sum_n x_i {S_i}^2}{\sum_n {S_i}^2} \qquad (1)$$

where x is the mean position (RA, Dec.) or velocity of the maser component, S_i is the peak flux in channel i and x_i is the position or velocity of the maser component in channel i. $\sum_n$ is the sum over all the channels containing the maser component. Maser peak velocities were determined similarly, by calculating the weighted mean velocity of the set of brightest channels over which the mean position was calculated.

3. Results

We observed W3(OH) in the hyperfine lines of the $^2\Pi_{1/2}$, J=1/2 rotational energy level at 4765, 4750 and 4660 MHz using MERLIN with phase-referencing and produced maps using a 50 × 50 mas synthesised beam. We detected OH 4765-MHz maser spots A, B and C at the same positions and velocities as Gray et al. (2001) within experimental uncertainties. We detected no emission or absorption at 4750 or 4660 MHz. MERLIN detected all the 4765-MHz flux, but most of the flux near –44.5 km s^{-1} was extended and weak, ≤ 40 mJy beam^{-1}. We then re-mapped the 4765-MHz data with a larger (100 mas) synthesised beam in the hope of observing the extended emission. We discovered a large-scale filament that extends ∼1 arcsec (∼2200 AU) between the previously observed OH maser spots A and B. An OH maser feature of this size and nature is completely unprecedented, especially at MERLIN resolution where maser spots usually have very simple structures. The maps made with a 100 mas synthesised beam also reveal weak elongated haloes around all three spots A, B and C suggesting that these may also be filamentary in nature. We applied a round of phase self-calibration in order to improve the signal-to-noise ratio of the maps and to ensure the quality of the OH 4765-MHz filament maps. A contour map showing the filament, together with some emission from spots A, B and C, integrated over the velocity range –43.5 to –44.8 km s^{-1}, is shown in Figure 1. The peak brightness temperature of the filament is ∼ 4 × 10^5 K.

The OH filament has a systematic velocity gradient which is shown in Figure 2. This displays the region of the filament in the Declination-Velocity plane with channels of decreasing RA. The filament, which stretches between OH 4765-MHz maser spots A and B, is clearly curved in the velocity plane (shown along the ordinate axis). A similar velocity gradient was noted by Wright et al. (2004a) and was interpreted by them as evidence for a rotating disc structure. A disc interpretation was also proposed much earlier by Guilloteau, Baudry & Walmsley (1985).

4. Discussion

The OH 4765-MHz maser filament presented in this paper clearly corresponds with arcs of OH ground-state masers found by Wright et al. (2004b). Those authors noted several arcs of emission and showed that individual maser spots were elongated along those arcs. The OH filament is shown in greyscale in Figure 3, overlaid on the data of Wright et al. (2004b). The central section of the OH filament is associated primarily with an arc of OH 1665-MHz masers which extend a further ∼400 mas to the South of the filament. The velocity gradient of the filament, from –45.0 km s^{-1} in the North to –44.3 km s^{-1} in the South, also matches that reported at 1665 MHz (Wright et al., 2004a). The authors suggested that this arc at 1665 MHz, and others to the South at 1667 MHz, may trace large-scale shocks. The narrowness of the 4765-MHz filament suggests a shock on an even larger scale (2200 AU assuming a distance of 2.2 kpc.).

The OH filament appears to be embedded within extended OH 4750-MHz quasi-thermal emission and 4660-MHz absorption detected in W3(OH) by Guilloteau et al. (1985). These occur because the mechanism of FIR radiative trapping between the $^2\Pi_{1/2}$, J=3/2 and J=1/2 rotational levels is thought to lead to an overpopulation of the F=1 levels relative to the F=0 levels

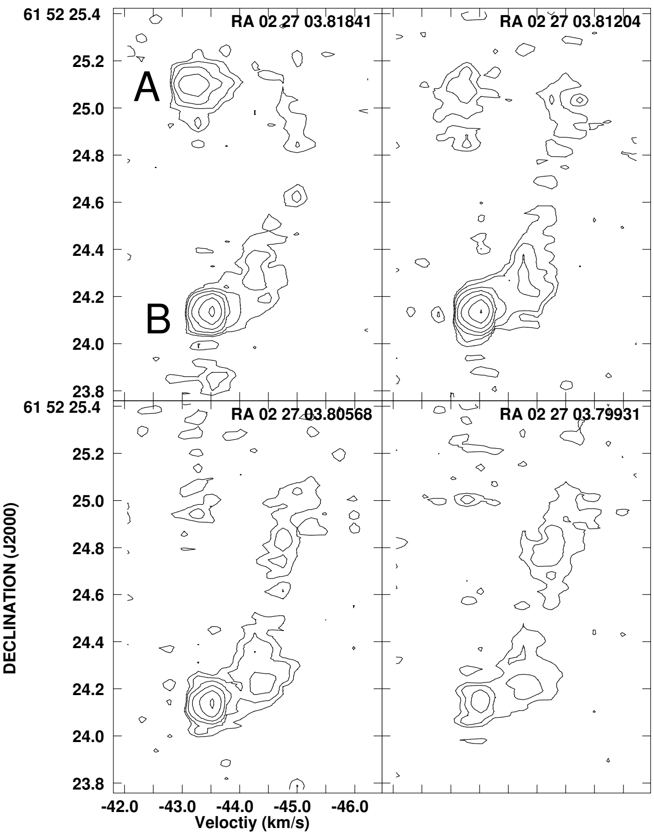

Fig. 2. Velocity-declination plots of the OH 4765-MHz maser filament in W3(OH), showing the velocity gradient of the filament between spots A and B. Contour levels are 12.0 × (1, 2, 4, 8, 16, 32) mJy beam^{-1} .

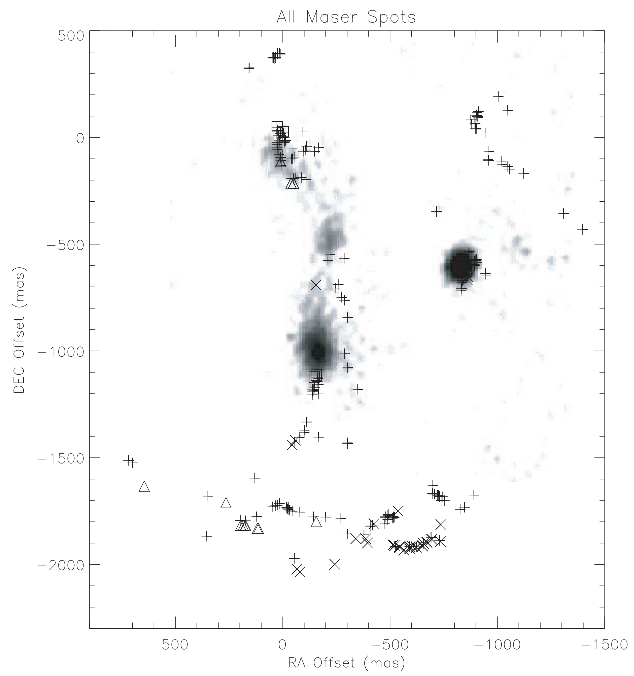

Fig. 3. OH 4765-MHz emission (greyscale) integrated from -44.0 to -44.8 km s^{-1} showing the excited OH filament together with some emission from spot C, superimposed on the locations of the 18-cm masers mapped by Wright et al. (2004b), adapted from their Figure 10. The symbols denote 1612-MHz (△), 1665-MHz (+), 1667-MHz (×) and 1720-MHz (□) masers.

(Litvak et al., 1969; Elitzur, 1977; Gardner & Martin-Pintado, 1983; Guilloteau et al., 1985). This means that the F=1 levels are overpopulated relative to F=0 and hence the (F=1–0) 4765-MHz and (F=1–1) 4750-MHz lines are inverted (strongly and weakly respectively), whereas the (F=0–1) 4660-MHz line is anti-inverted and seen in absorption. The 4750-MHz emission at –44.5 km s^{-1} peaked near spot A and extended South roughly along the filament. The 4660-MHz absorption showed a similar pattern at –44.5 km s^{-1}, but peaked in the South near spot B and extended North along the filament. We searched for absorption in our data at 4660 MHz but found nothing, although given the weak OH 4765-MHz emission in this region between spots A and B this suggests that the 4660-MHz line would be weakly anti-inverted and consequently, the 4660-MHz absorption would also be weak. Extended absorption and/or emission from many other transitions of highly-excited OH are seen in this North-South corridor of W3(OH), including 7820, 7762, 8136, 8190, 23818 and 23827 MHz. Figure 4 shows the OH 4765-MHz filament in greyscale alongside corresponding examples of extended OH absorption and/or emission features.

There has been growing evidence for shock structure in the OH masers of W3(OH). Baudry and Diamond (1998) detected arcs of OH masers at 13.44 GHz including a small OH filament only ∼15 mas long. This type of elongated maser morphology was also noted by Wright et al. (2004a) at 1665 MHz. Linear structures have also been reported in methanol masers (Norris et al., 1993). Dodson, Ojha and Ellingsen (2004) argue that these are evidence for edge-on shocks propagating almost perpendicularly to the line-of-sight.

Observations of our much larger OH 4765-MHz filament at VLBI resolution could help us to determine whether any smaller-scale structure is present. Palmer, Goss & Devine (2003) observed W3(OH) using the VLBA and detected no emission in the "plateau" between the two spectral maxima at –44 km s^{-1}. Given the very high resolution of the VLBA, this suggests that if the filament is composed of high brightness cores, these would have to be extremely compact (much less than 3 mas). Assuming then that the OH 4765-MHz maser emission is truly extended, this signals a departure from the usual observations of OH 4765-MHz masers as compact spots.

Methanol masers show evidence for core-halo structure. Minier, Booth and Conway, (2002) studied the milliarcsecond structure of methanol 6.7 and 12.2 GHz masers using the EVN and VLBA respectively. They found that the majority of individual maser spots displayed a compact-core/extended-halo structure. The cores varied between 2-20 AU and the extended emission ranged from 12-290 AU. Possible explanations for this structure include velocity turbulence, masing pockets of gas separated from the core, and beaming effects related to maser saturation.

Cesaroni & Walmsley (1991) have modelled the excitation of all OH lines up to 512 K above the ground state, with particular application to W3(OH). They obtained 4765-MHz in-

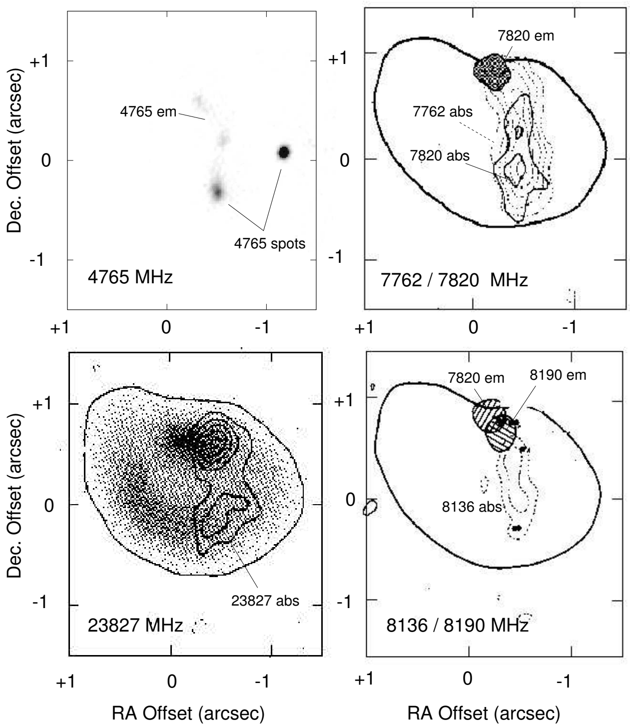

Fig. 4. Montage of absorption/emission maps of W3(OH) showing the relative positions of absorption and emission features. The top left panel shows the OH 4765-MHz filament in greyscale, integrated between –44.0 and –44.8 km s^{-1}. The top right panel from Baudry et al. (1993) shows 7762- and 7820-MHz absorption, and 7820-MHz emission. The bottom left panel is from Baudry & Menten (1995) and shows absorption OH 23.8 GHz contours overlayed on the 23-GHz radio continuum emission (greyscale). The bottom right panel, from Baudry et al. (1993), shows OH emission at 7820 and 7190 MHz, and absorption from OH at 8138 MHz. Co-ordinate offsets are relative to RA (J2000) 02 27 03.8812, Dec.(J2000) +61 52 24.572.

version over a wide range of densities up to 10^8 cm^{-3}, with $T_{gas} = T_{dust} = 151$ K (their Fig. 10), together with 4660-MHz anti-inversion and weak 4750-MHz inversion. Their model can account for most of the OH observations up to 23 GHz.

The 4765-MHz OH filament appears to be a narrow structure, possibly tracing a shock front, that is embedded within the much more widespread OH cloud traced by the weakly masing 4750-MHz emission and the 4660-MHz absorption. The fact that the 4765-MHz OH filament is seen in projection against the (optically thick) HII region means that the maser gain can still be modest, as low as 40. However hotspots with size less than 3 mas and much higher gains are not excluded, as mentioned earlier.

It is certainly remarkable to note the spatial and velocity agreement between the OH 1665-MHz arc, the highly-excited OH absorption/emission features and the OH 4765-MHz maser filament.

5. Conclusions

We have made observations of the three hyperfine lines from the $^2\Pi_{1/2}$, J=1/2 rotational energy level in the OH-HII region W3(OH) with phase-referencing using MERLIN. The 4750- and 4660-MHz lines were non-detections, but we detected all the flux (3.9 Jy km s^{-1}) at 4765 MHz. This was in the form of three maser spots and a large, low-brightness OH maser filament stretching 2200 AU between two of the spots. There was also extended 'halo' of emission around the cores of all three 'spots'. This type of core-halo structure is normally associated with methanol masers. Previous VLBA observations failed to detect the OH 4765-MHz filament, which suggests that this is a truly extended source of emission. The 4765-MHz OH filament is closely associated with an arc of ground-state OH 1665-MHz masers and absorption/emission lines of highly-excited OH up to 511 K above the ground state. We interpret this feature as a large-scale shock propagating in an edge-on rotating disc. Future MERLIN plus EVN studies will hopefully clarifiy the nature of this filament and the physical processes involved in its excitation.

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