Magnetic field strengths from polarimetric VLBI observations of water masers in W51 M

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Introduction

The idea that interstellar magnetic fields are coupled to gas motions was first discussed by Alfven (1943) and Fermi (1949). Magnetic fields reveal themselves by polarizing radiation. According to the classical maser polarization theory (Goldreich et al., 1973a, 1973b), maser polarization is linear if the stimulated emission rate of a saturated maser is smaller than the Zeeman splitting rate, which on the other hand should be smaller than the linewidth of the amplified radiation. This is generally the case for water masers.

Powerful 22 GHz water masers are commonly associated with energetic protostellar outflows. Shocks with velocities exceeding some 20 km s^{-1} running into high-density magnetized material successfully explain the water maser emission associated with outflows from young stellar objects (Hollenbach and McKee, 1989; Elitzur et al., 1989).

Here we summarize the main results of Leppänen, Liljeström, and Diamond (1998), who reported the first 22 GHz linear-polarization VLBI images (obtained with VLBA) of low-velocity water masers in the star-forming region W51 M. The spatial and spectral resolution obtained were 0.3 milliarcseconds (mas) and 0.2 km s^{-1}, respectively. The principal difference of polarimetric VLBI from total intensity VLBI is the need to calibrate the instrumental polarization parameters, which have been solved by Leppänen (1995) with a feed self-calibration algoritm.

Kinematic and linear polarization structure of water masers in W51 M

Figure 1a shows the spatial distribution of the low-velocity ($54 < V_{lsr} < 68$ km s^{-1}) water maser spots. Superimposed on the spots are the linear polarization vectors with their lengths proportional to the degrees of polarization. The inset of Figure 1a is an enlargement of the compact maser concentration near the reference position (0,0) of W51 M. The dotted line in the inset separates blueshifted (west of the dotted line) and redshifted (east of the dotted line) maser spots with respect to the velocity centroid, 61.5 km s^{-1}, of this maser concentration, hereafter called the protostellar cocoon. With a distance of 7.0 kpc to W51 M, the inner and outer radii of this maser cocoon are approximately 5 AU and 66 AU, respectively.

Besides the maser cocoon, Figure 1a reveals a 1200 AU long linear maser structure at a position angle, P.A., of 200°. This structure, which is blueshifted some 5 km s^{-1} with respect to the protostar, is roughly aligned with the Galactic magnetic field projection on the sky, P.A. = 205° (Matthewson and Ford, 1970; Mufson and Liszt, 1979) and the polarization position angle of these masers (median EVPA = 197°). The proper motion vectors, presented in Figure 1b, show that these masers move longitudinally along this direction with a median space velocity of 25 km s^{-1} relative to the centroid of the cocoon. The proper motions exclude the interpretation of this large-scale streamer as a low-velocity bipolar outflow from W51 M. Most likely the stream is produced by shocks caused by the nearby expanding HII region, W51 IRS 1, which interacts with the dense molecular core of W51 M on its western side.

In contrast to the cocoon masers, which show a mean linear polarization of only 3% (maximum 13%), the masers in the streamer exhibit higher degrees of linear polarization (mean 12%; maximum 35%). This is in good agreement with the classical maser polarization theory (Goldreich et al., 1973a, 1973b), which predicts linear polarization degrees between 0 and 1/3. The cocoon masers show larger velocity dispersions and smaller flux densities than the streamer masers. While for cocoon masers the degree of linear polarization tends to decrease with increasing velocity dispersion of a spot, the polarization degree of the streamer masers is independent of the velocity dispersion inside a spot.

Magnetic field strength of the large-scale streamer

The direction of the linear polarization of saturated masers is predicted (Goldreich et al., 1973a) to be parallel (perpendicular) to the magnetic field projection on the sky if the angle between the field and the line-of-sight is less than 55° (over 55°). Since the line-of-sight toward the HII region W51 is roughly tangential to the Sagittarius spiral arm (see Fig. 10 of Mufson and Liszt, 1979), linear polarization parallel to the field is expected.

The good alignment of the linear polarization vectors of the large-scale streamer suggests that the turbulent motions in the medium are more wavelike than eddylike. Since turbulent velocity fields produced by shocks induce turbulent magnetic fields, the level of magnetic fluctuations is related to the associated fluctuations in kinetic energy by the principle of equipartition (Whitham, 1974). This enables us to estimate the preshock magnetic field strength of the streamer indirectly from the relation, $\delta B/B = \delta V/\mathrm{V}_A$, where $\mathrm{V}_A = \mathrm{B}/(4\pi\ \rho)^{0.5}$ is the Alfven velocity (ρ is the mass density of the medium). The left-hand side of this relation ($\delta B/B$) determines the angular deviation, $\delta\phi$, of the linear polarization vectors from the magnetic field direction and can be replaced with it. If the velocity fluctuation, δV, is random, as in turbulence, then the above relation can be averaged over all data points yielding an Alfven velocity, $\mathrm{V}_A = \delta V_{rms}/\delta\phi_{rms}$, of 1.1 (±0.23) km s^{-1}. This corresponds to a magnetic field parameter, $\mathrm{b} = \mathrm{V}_A/1.84$ km s^{-1} (Hollenbach and McKee, 1989), of 0.6. The relation $\mathrm{B}_o = \mathrm{b}(\mathrm{n}_o)^{0.5}\ \mu$ G (Hollenbach and McKee, 1989) yields thus a preshock field strength of 1.2 (±0.25) mG. In the above relation, the preshock hydrogen nuclei density of W51 M, $\mathrm{n}_o = 3.8 \times 10^6$ cm^{-3}, was adopted from Plume et al. (1997).

Inside the masing regions of the streamer, the strength of the magnetic field is relatively independent of the preshock field strength, since the magnetic pressure (which is determined by the ram pressure of the shock) dominates in the masing region (Hollenbach and McKee 1989). In addition, since the emission after a shock front occurs in the observer's frame in the range $(3/4)\mathrm{V}_{shock} < \mathrm{V}_{space} < V_{shock}$ (Hollenbach et al. 1989), the space velocities of masers should closely trace shock velocities. Thus, with the observed median space velocity of the streamer masers, 25 (±8.4) km s^{-1}, a characteristic magnetic field strength of 38 (±15) mG results inside the masing regions of the streamer (using eq. [4.6] of Elitzur et al., 1989, which depends on the shock velocity and preshock density).

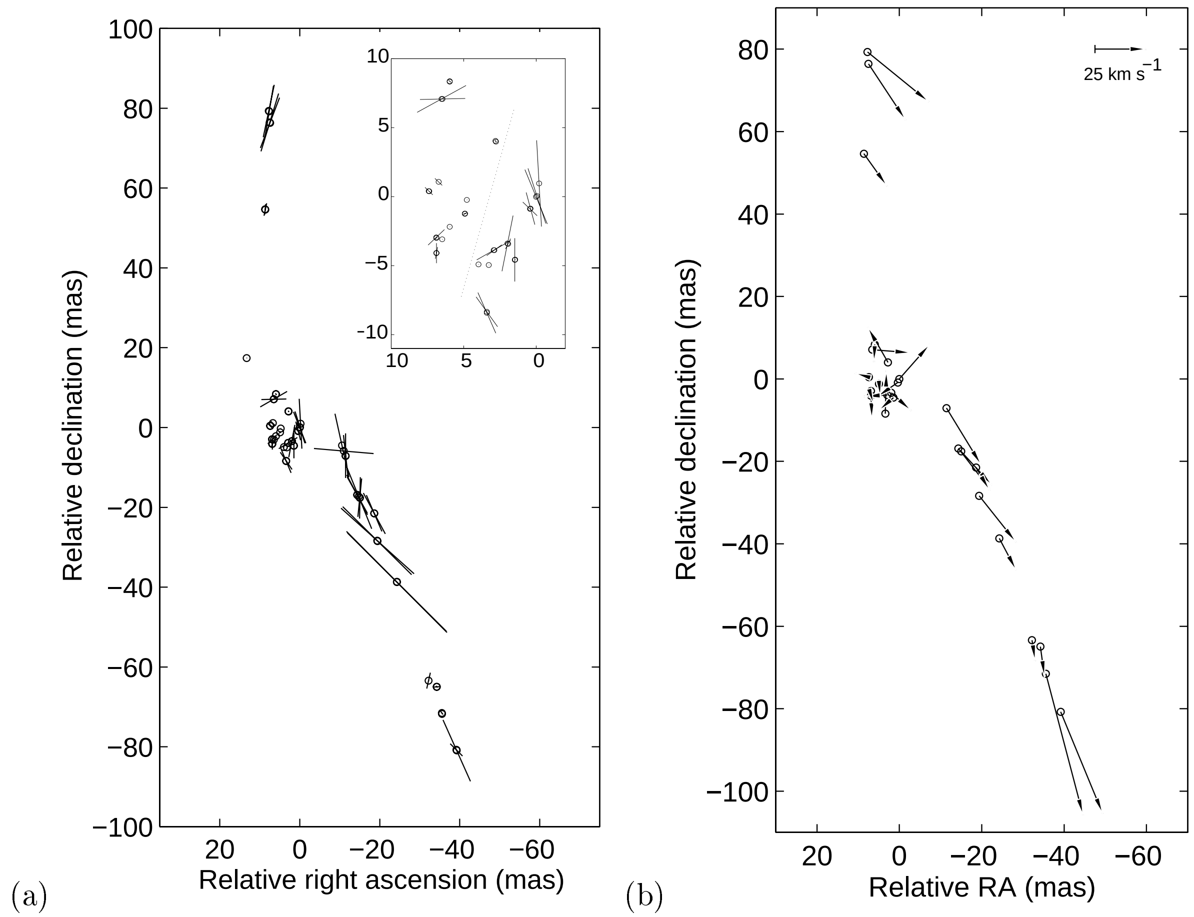

Figure 1: *Left (a):* The first VLBI linear polarization image of water masers in W51 M. The lines show the direction of the linear polarization; their lengths are proportional to the polarization degrees of the spots (1 mas = 1%). The inset is an enlargement of the protostellar maser cocoon near the reference position (0,0) of W51 M (polarization lines: 1 mas = 2%). 1 mas corresponds to 7 AU. *Right (b):* Proper motion vectors of the observed water masers in W51 M. The motions are relative to the centroid of the cocoon masers

Conclusion

Sub-milliarcsecond linear polarization results of 22 GHz water masers in W51 M were presented. We showed that for the large-scale linear polarization structure found in W51 M (the streamer) both preshock and postshock magnetic field strengths can be determined from VLBI linear polarization and proper motion measurements because the preshock hydrogen nuclei density of the medium is known. For the streamer of W51 M, a preshock field strength (perpendicular to the shock velocity) of 1.2 (±0.25) mG resulted. Inside the masing regions of the streamer the typical total field strength is 38 (±15) mG.

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