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Zeeman splitting in OH megamasers

Timothy Robishaw, Carl Heiles, and Eliot Quataert

Department of Astronomy, University of California, Berkeley, CA 94720, USA

Abstract. We detected significant Zeeman splitting in the 1667 MHz OH megamaser emission from four ultraluminous galaxies. These detections, in addition to being the first extragalactic detection of the Zeeman effect in an emission line, suggest that OH megamasers are excellent extragalactic magnetometers.

Keywords. Masers, galaxies: magnetic fields, galaxies: starburst, ISM: molecules

1. Introduction

Ultraluminous infrared galaxies (ULIRGs) are a population of galaxies that emit far-infrared (FIR) radiation with energies comparable to those of the most luminous quasars ($\log(L_{\rm FIR}/L_\odot) > 12$). Nearly every ULIRG appears to have undergone a merger/interaction and contains massive star formation and/or an active galactic nucleus (AGN) induced by gravitational interactions. Diamond *et al.* (1999) conducted very long baseline interferometry (VLBI) observations of the 1667 MHz hydroxyl (OH) transition in the nuclear regions in ULIRGs and found multiple masering regions with $1 < \log(L_{\rm OH}/L_\odot) < 4$; these regions are known as OH megamasers (OH MMs). Each OHM has a spectral linewidth of between 50 and 150 km s^{-1}; when viewed by a single dish, these spectral components are superimposed. The 1667 MHz OHM flux is always a few to many times the flux of the 1665 MHz transition and in many cases the 1665 MHz line is absent (Darling & Giovanelli 2002); this is an interesting contrast to the case of OH masers in the Galaxy in which the 1665 MHz is usually the dominant transition (Reid & Moran 1988). The starbursts and AGNs in ULIRGs create strong FIR dust emission as well as a strong radio continuum; the OHMMs are generally believed to be pumped by the FIR radiation field (e.g., Randell *et al.* 1995) although collisional excitation may be important as well (e.g., Lonsdale *et al.* 1998). Given the conditions that exist in ULIRGs and considering that every OH maser in our Galaxy is associated with massive star-forming regions, it is not surprising that the entire OHM sample finds homes in LIRGs, strongly favoring the most FIR-luminous, the ULIRGs (Darling & Giovanelli 2002).

ULIRGs are natural locations to expect very strong magnetic fields given their high gas and energy densities. Much of the radio emission in ULIRGs is resolved on scales $\sim$ 100 pc with VLA observations (Condon *et al.* 1991). In Arp 220, high-resolution observations (Rovilos *et al.* 2003) show that the OH MMs arise in this region as well. With this size scale and the observed radio fluxes, minimum energy arguments suggest *volume averaged* field strengths of $\approx$ 1 mG (e.g., Condon *et al.* 1991, Thompson *et al.* 2006), significantly larger than the $\sim 10\mu$G fields measured in normal spirals. The field strengths in ULIRGs cannot be much below a mG or else inverse Compton cooling would dominate over synchrotron cooling, making it energetically difficult to explain the radio fluxes from ULIRGs and the fact that ULIRGs lie on the FIR-radio correlation. The field strengths could, however, in principle be larger than the minimum energy estimate if, as in our Galaxy, the magnetic energy density is in approximate equipartition with the total pressure (Thompson *et al.* 2006). This can be estimated from the observed surface density; CO observations of Arp 220 and several other systems reveal $\sim 10^9 M_\odot$ of molecular gas in the central ~ 100 pc (e.g., Downes & Solomon 1998) implying gas surface densities $\Sigma \sim 1 - 10\,\mathrm{g\,cm^{-2}}$, $10^3 - 10^4$ times larger than in the Milky Way. The equipartition field scales as $B \propto \Sigma$ implying that the mean field in ULIRGs could approach $\sim 10\,\mathrm{mG}$.

2. Observations

Motivated by the above considerations, we have used the 300 m Arecibo† telescope in full-Stokes mode to try to detect Zeeman splitting in megamaser emission of the 1667 MHz OH transition. The six strongest OH MMs visible from Arecibo were observed by spending equal time at on-source and off-source positions. As shown by all VLBA observations of OH MMs, the spatial extent of the OHM emission in any ULIRG is much smaller than Arecibo's beam; there are no instrumental polarization effects due to beam structure or sidelobes. The observations were made in full-Stokes mode and the Mueller matrix was calibrated using the standard Arecibo technique of observing the linearly-polarized continuum sources 3C138 and 3C286 (Heiles *et al.* 2001, Heiles & Troland 2004).

3. Results

Four of the six sources we observed exhibit significant Stokes V emission that can be interpreted as Zeeman splitting of the 1667 MHz line. We present the results for IRAS F12032+1707, one of only 3 known gigamasers, in Figure 1. The top panel shows the Stokes I spectrum‡ of the source as a function of frequency and optical heliocentric velocity (this source is at $z = 0.217$). It is clear that the OHM emission profile is a composite of many narrower components as the emission spans almost 2000 km s^{-1}. The 1665 and 1667 MHz lines are blended in this source. We decomposed the Stokes I profile into 13 Gaussian components; we attempted to use the fewest number of components to obtain reasonable residuals (which are plotted with an enhanced scale through the middle height of the Stokes I profile) while allowing enough components to reproduce multiple splittings in the Stokes V spectrum. The bottom panel shows the Stokes V spectrum and it is clear that the detectable circular polarization is restricted to the stronger of the two bright and narrow Stokes I peaks. The fitted field for this feature is $17.9 \pm 0.8\,\mathrm{mG}$.

A total of 15 independent field detections were made in multiple components within four extragalactic sources including Arp 220 and III Zw 35. The median absolute field strength is $\sim 3\,\mathrm{mG}$ and the direction of the field reverses within 3 of the galaxies. It is interesting to note that the standard deviation of the magnetic field distribution of the Galactic OH masers is also $\sim 3\,\mathrm{mG}$ (Fish *et al.* 2003).

4. OH megamasers: the new extragalactic magnetometers

The Zeeman detection rate for our sample of ULIRGs suggests that OH MMs are excellent extragalactic magnetometers. Since it is not possible to unambiguously associate

† The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation.

‡ We use the classical definition of Stokes I, which is the sum (not the average) of two orthogonal polarizations. Thus, fluxes in Stokes I are twice the usual flux density given in catalogs.

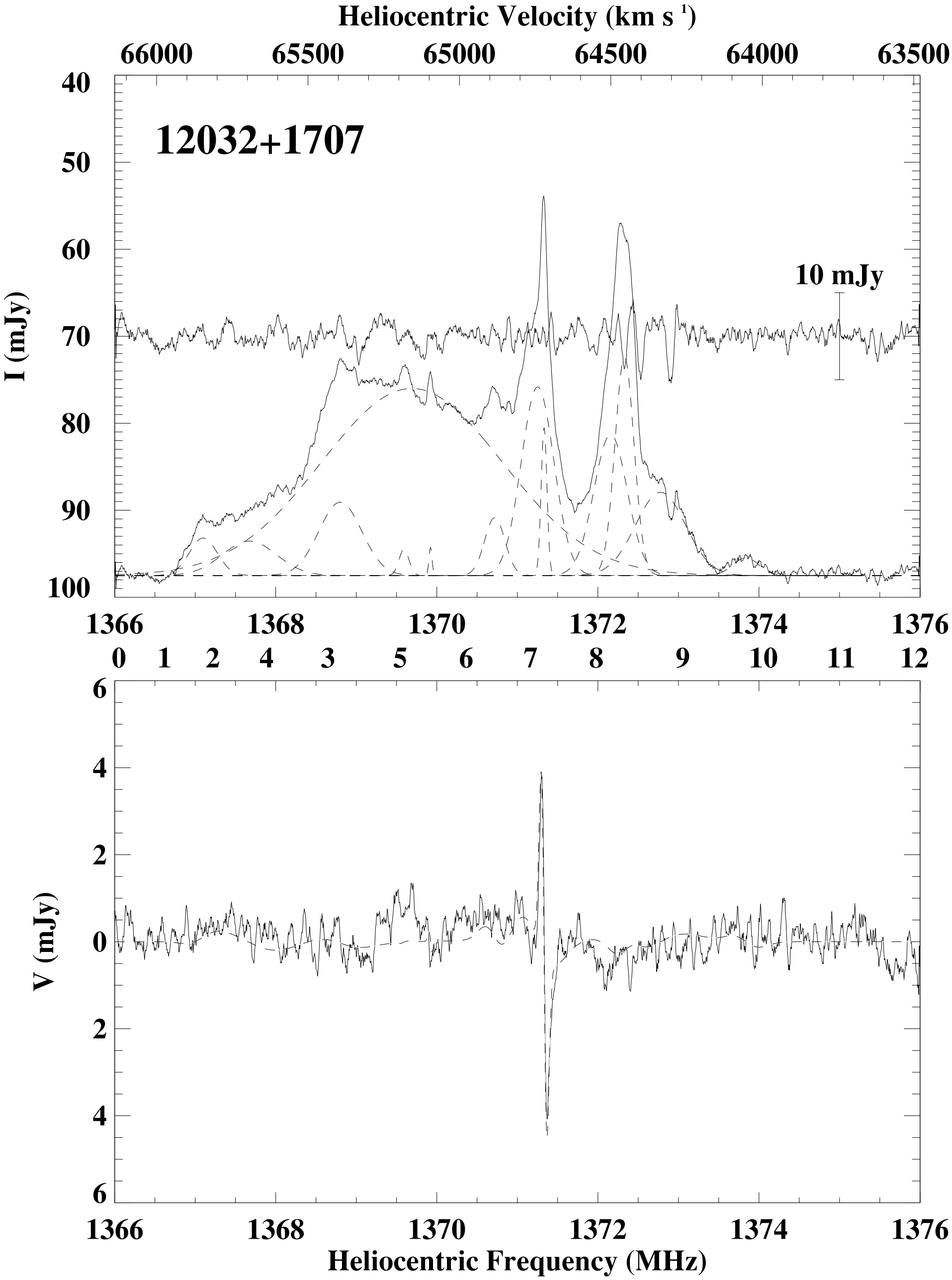

Figure 1. Stokes I spectrum (*top*) for IRAS F12032 + 1707. The residuals are plotted through the center of the Stokes I plot and are expanded by a factor of 2. The profile of each Gaussian component is plotted as a dashed line. The Stokes V (*bottom*) spectrum with its fit is plotted as a dashed line.

the VLBA spectra of the OH MM spots within any ULIRG with the Gaussian components in our single-dish spectra, we shall be observing Arp 220 and III Zw 35 using the High-Sensitivity Array configuration of the VLBA in order to attempt to detect Zeeman

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splitting directly in the OH MM spots. We shall also conduct a full-Stokes flux-limited Arecibo survey of OH MMs including the OH satellite lines.

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