OH Megamasers, Ultraluminous Infared Galaxies, and Magnetic Fields

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 ($\log(L_{\rm FIR}/L_\odot) > 12$; Pihlström 2005). 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 1667 MHz VLBI observations of the nuclear regions in ULIRGs and found multiple masing regions with $1 < \log(L_{\rm OH}/L_\odot) < 4$; these regions are known as OH megamasers (OHMs). Each OHM has a spectral linewidth between 50 and $150\,{\rm km\,s^{-1}}$. The starbursts and AGN in ULIRGs create strong FIR dust emission as well as a strong radio continuum; the FIR radiation field inverts the OH population by pumping, then the maser is stimulated by 18-cm continuum. Given the conditions that exist in ULIRGs and considering that every OH maser in our own 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).

The extraordinarily high gas densities and energy densities in ULIRGs make them natural locations to expect very strong magnetic fields. With the observed radio continuum fluxes in ULIRGs, minimum energy arguments suggest characteristic field strengths $\sim 100\,\mu$G and equipartition suggests 1 to 10 mG. In our own Galaxy, the magnetic field observed in regions of OH maser emission is significantly larger than the mean (equipartition) Galactic field (Fish et al. 2003). Therefore, we expect with some confidence that the OHMs in ULIRGs will display large, easily-detectable magnetic fields with Zeeman splitting.

Robishaw, Heiles, & Quataert (2007) confirm this prediction. They observed Stokes V spectra for OHMs in 6 ULIRGs and found clear, unambiguous Zeeman splitting in 4 of them. Each ULIRG typically has several or more recognizable narrow OHM components visible in Stokes I, and for the minority that also have detectable Stokes V one obtains the line-of-sight magnetic field strength. In the 4 ULIRGs there were a total of 43 discernable OHMs, of which 16 had unambiguous ($> 3\sigma$) detections of magnetic field. These exhibited line-of-sight field strengths ranging from 0.3 to 20 mG, a range comparable to that of Galactic OH masers. These Arecibo observations increased the sample of extragalactic Zeeman-splitting detections by a factor of 17 (the only previous detection was a weak field in an absorption HI line by Sarma et al. 2005). Previous attempts to detect Zeeman splitting of OHMs failed because of lack of sensitivity (Killeen et al. 1996)—failures resulting from using smaller, less sensitive telescopes (ATCA) and a less-than myopic obsession with getting detections.

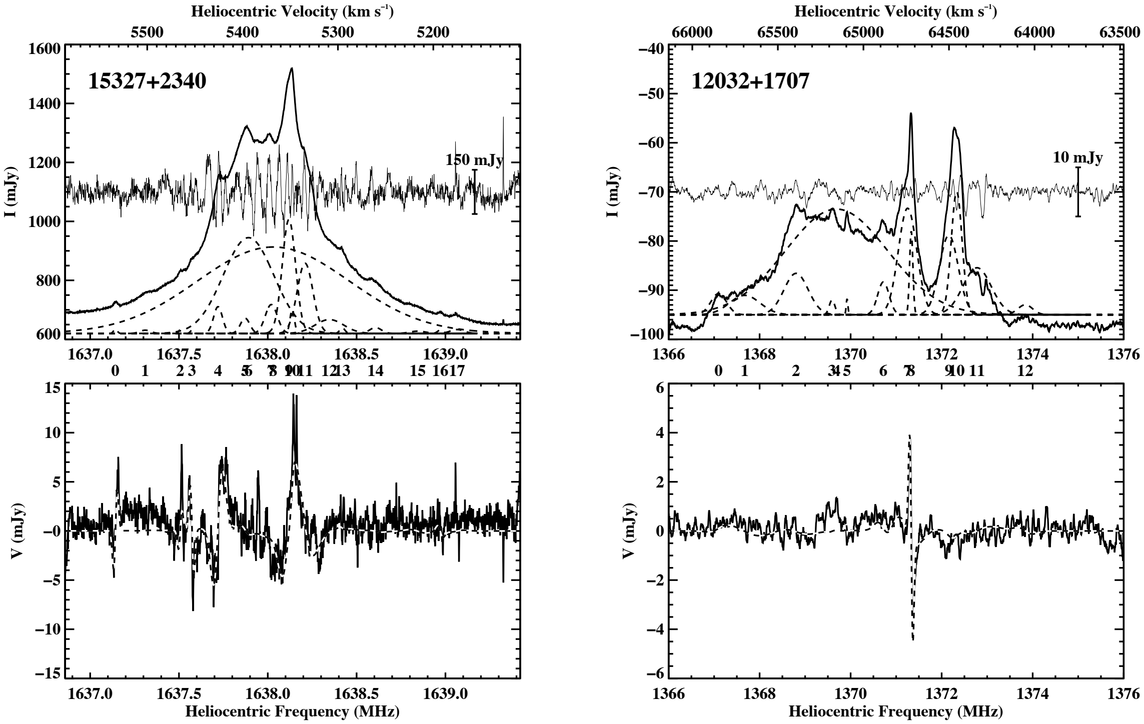

Fig. 1.— (*Left*) OHM emission from Arp 220. The top plot shows Stokes I with components from a Gaussian deconvolution as dashed lines. The solid line in the center of the vertical axis shows an inflated view of the Stokes V residuals after fitting for magnetic field. The bottom plot shows Stokes V with the best fit plotted as a dashed line. The integers shown between the top and bottom plots label the Gaussian components. (*Right*) OHM emission from the gigamaser IRAS F12032+1707.

Figure 1 exhibits the OH Stokes I (top) and V (bottom) spectra for two of our four galaxies. The left panel shows the archetypical ULIRG Arp 220 and the right the $z = 0.22$ gigamaser galaxy IRAS F12032+1707. The I spectra for both galaxies show numerous narrow components that are fit with Gaussians—a total of 17 for Arp 220 and 12 for F12032+1707. Many of the narrow components in Arp 220 exhibit strong signals in Stokes V, with the result seeming to resemble an incomprehensible jumble. Nevertheless, it is straightforward and surprisingly unambiguous to fit the Stokes I Gaussians with individual magnetic fields. 6 of Arp 220's 17 components have detectable fields whose line-of-sight strengths range from 0.3 to 4.8 mG.

F12032+1707 is a completely different story. Only 2 of its 12 components have detectable Zeeman splittings—but what a signal! The Gaussians have line-of-sight field strengths $10.9\pm$

1.6 and 17.9 ± 0.8 mG. The comparison of Stokes V signals in these two ULIRGs offers a big surprise. The peak fractional circular polarization for Arp 220 $\sim 1.8\%$. In contrast, for F12032+1707 it's $\sim 9.5\%$, more than 5 times larger. Thus, despite the fact that its Stokes I line is 20 times weaker than for Arp 220, the signal/noise for Stokes V is also huge!

We want to survey as many ULIRG OHMs as possible for magnetic fields; we discuss the scientific rationales below. How deep should we push such a survey? The Stokes I line strength for F12032+1707 is about 40 my. The signal/noise in its Zeeman-splitting Stokes V spectrum is ~ 22. This shows that we can usefully push down to ~ 2 mJy in Stokes I. However, consider that we have here only a tiny sample of ULIRGs with OHMs. It is unlikely that this sample happens to contain the one ULIRG—F12032+1707—with the highest detectable Stokes V in the entire list of ULIRGs that contain OHMs. Indeed, most Galactic OH masers have splitting that exceed the line width, in which case the Stokes V signal is equal to the Stokes I signal—they can exhibit 100% circular polarization! Any ULIRG for which this happens will also display huge fractional circular polarization. This argues that we should examine the *complete list* of OHM-containing ULIRGs, whose Stokes I flux densities range down to 2 mJy. There are about 100 such galaxies, of which 73 are visible from Arecibo.

Why is this scientifically important? 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. Observations across many spectral windows have revealed hot, X-ray emitting gas, relativistic electrons, molecular clouds, and the effects of rapid, large-scale star formation. We know a lot about kinematics and the spatial structure of the stars and the various gas components. However, we have virtually *no* knowledge about the magnetic fields[1]. Measuring magnetic fields in OHMs provides information on two scales:

1. The small scales of the masers themselves, which provide information on how the star formation process and magnetic forces interact.
2. The large-scale field in the interacting regions where the OHMs reside. Fish et al. (2003), with their comprehensive survey of Galactic OH masers and the accompanying statistical discussion, strongly support several previous suggestions that (surprisingly enough) the field *direction* in OH masers usually mirrors that of the large-scale field in the vicinity of the masers. Thus, we can use the measured field directions in OHMs to map the field direction in the larger-scale interacting regions *themselves.*

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[1] Not only ULIRGs!

Point 1 above is important for our understanding of star formation and the behavior of magnetic fields in dense regions. We would like to establish just how strong field strengths can become in OHMs. In the Milky Way, just a few short years ago the maximum known field strength in OH masers was $\sim$ 10 mG. However, Slysh & Migenes (2006) discovered much higher field strengths, 40 mG in W75, which was confirmed by Fish & Reid (2007). These superhigh field strengths in Galactic masers occur only in the fairly rare time-variable, flaring OH maser components. Darling (private communication) observes similar time-variable components in OHMs, and it seems likely that these flaring OHM components will also have anomalously high field strengths. We believe it is important to establish whether the magnetic field range in OHMs extends to these limits and whether the correlation between magnetic field strength and time variability persists in the ULIRG environment.

Point 2 above is perhaps even more important. Many of these interacting systems exhibit clumps or rotating regions whose dynamics are a direct result of the interaction between two galaxies. OHM Zeeman splittings provide the opportunity to determine the role of the magnetic field in the interaction and the subsequent dynamics.

Interpreting the fields in terms of the large-scale dynamics requires knowing in which parts of the interacting region the OHMs are located. To some extent, this can be gleaned from single-dish spectra because the interacting regions often contain large velocity gradients, so the typical velocity is associated with a typical part of the interacting region. However, this association is less than perfect because the velocity dispersions at any one position are large. We expect the survey information to be useful as a statistical indicator. For example, in Arp 220 there is a tendency for the line-of-sight field directions to be opposite on the two halves of the velocity interval covered by the individual OHMs, which can be interpreted as a tendency for the field to reverse on opposite sides of the rotating disk.

The only *sure* way to establish these connections in individual cases is with VLB maps of the OHMs, so that individual field detections can be pinpointed on the map to reveal clear, unambiguous associations. VLB observations suffer from sensitivity. To study individual cases we need, first, a comprehensive single-dish survey to establish which particular ULIRGs exhibit large Stokes V (not Stokes I) spectra and use the best examples as subjects of intensive, high-sensitivity VLB maps. The VLB observations themselves will need as much sensitivity as possible, which also means using Arecibo—as part of the VLB array.

In summary, we see Arecibo as a vital link in the study of extragalactic star formation and magnetic fields in interacting galaxies.

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