DIRECT IN SITU OBSERVATIONS OF MAGNETIC FIELDS IN GALAXIES AT INCREASINGLY HIGH REDSHIFTS

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1. INTRODUCTION: DIRECT, IN SITU MEASUREMENTS OF MAGNETIC FIELDS IN ACTIVE GALAXIES

Optical and radio polarization studies have established that the Milky Way and many nearby spiral galaxies have well-organized, large-scale magnetic fields (see Beck et al. 1996). The presence of coherent magnetic fields on large scales points to a powerful, ubiquitous process which organizes random motions into highly ordered structures. Galaxies and clusters of galaxies are likely formed from collisions of smaller constituents, and then are continually energized by galaxy mergers, stellar winds and supernovae. Thus, it is remarkable that the magnetic fields produced by the resulting complicated gas ows and electrical currents are some of the largest organized structures in the Universe.

Observations of active galaxies across many spectral windows have revealed exotica such as hot, X-ray emitting gas, relativistic electrons, molecular clouds, and the effects of rapid, large-scale star formation. The major forces involved are gravity, pressure, and magnetic field. Observing the first two is relatively straightforward: we study gravity by measuring radiation and analyzing measured velocities, and we study pressure by measuring gas densities, temperatures, and random (turbulent) velocities. Such observational studies continue to be vigorously pursued by many groups and have produced a rich body of current results.

The third major force—the magnetic field—is not so well studied because it is notoriously difficult to measure. It's the field *strength* that's important, because this specifies the magnetic pressure. Most of our understanding of field strengths is uncertain because it is inferred from synchrotron radiation and Faraday rotation, neither of which is definitive: one needs to make a minimum-energy argument or guess at the electron density. Generally, inferred field strengths imply magnetic energy densities that are comparable to, or even exceed, gas thermal and turbulent pressure. This is true in many environments and size scales: high-z galaxies (Bernet et al. 2008), the global field in nearby galaxies (Beck 2008), and within galaxies down to scales of star formation (Heiles & Crutcher 2005).

The dynamo mechanism, in which small-scale turbulent magnetic fields are amplied and ordered by cyclonic motions and dierential rotation, is the preferred explanation to account for such structures, although dynamos are not fully understood and still face theoretical problems. The main rival is the *primordial* field theory, which assumes that the observed magnetic field patterns arise directly from a pre-galactic magnetic field distorted by galactic differential rotation.

A primordial field exists "in the beginning" because of an unspecified mechanism and, with flux freezing, gets stronger as galaxies condense out of the primordial soup. In contrast, a dynamo amplifies a "seed field" by a combination of flux freezing and magnetic reconnection occurring in the convectively-turbulent, differentially-rotating medium of a galaxy. Seed fields can be produced in a strictly zero-field situation, for example by the Biermann battery, or by black-hole dynamos that eject fields in extragalactic radio jets. Kulsrud (1999) is a principal proponent of the primordial-field concept and provides arguments why dynamos can't work; many other authors counter with elegant descriptions and modern models of functioning dynamos, the principles of which are well summarized by Parker (1979, 1997). Kulsrud & Zweibel's (2008) recent comprehensive review of these matters presents a clear, thorough and relatively balanced discussion of these matters at a considerable level of detail.

While the theorists can't agree, observers can clarify the situation by measuring magnetic field strengths at high redshift. Primordial fields depend on the density and don't evolve strongly with time, so their high-redshift strengths should be comparable to those in, say, the Milky Way. Dynamos, however, amplify the field bit by bit, so the field gradually becomes stronger until equilibrium between further field amplification and dissipative destruction is attained. Typical dynamo time scales depend on size scale: small-scale fields form first and they coalesce to form large-scale fields. The interesting range of redshifts spans $z \sim 0.5$ to ~ 3 (Arshakian et al. 2008).

We can make *direct*, in situ measurements of Zeeman splitting at such redshifts. Recent discoveries of Zeeman splitting in the 18-cm lines in OH Megamasers (OHMs) that reside in Ultraluminous Infrared Galaxies (ULIRGs; Robishaw, Quataert, & Heiles 2008) open wide new horizons for observational studies of magnetic field strengths, and even field directions. Currently, we have direct measurements of field strengths at redshifts ranging up to ~ 0.3 (with high signal/noise, too!), and as the sensitivity of radio telescopes increases in the future the redshift range available to these direct measurements will naturally expand.

2. ZEEMAN SPLITTING IN ULIRG OH MEGAMASERS

2.1. Important Preliminary: A Little-Known Trait of OH Maser Field Directions

Our understanding of the relationship between small- and large-scale magnetic fields has ballooned in recent years because of the detailed VLBA mapping of Zeeman splitting by Fish and collaborators (e.g. Fish et al. 2003). The OH maser field strengths are typically several milliGauss or more, stronger by orders of magnitude than the ambient field in their local environment. This field amplification occurs because of flux freezing: as the gas increases its density by orders of magnitude in the OH masers, the field is dragged along with it and also gets stronger.

A remarkable tendency occurs during the evolution of an OH maser. 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, measuring the direction of the field in an OH maser reveals the field direction not only *in* the maser, but also *outside and in the vicinity of* the OH maser. For the Milky Way, this aids us to infer the large-scale magnetic field morphology. The same should be true in other galactic environments.

2.2. ULIRG OH Megamasers

Many ULIRGs contain OH Megamasers (OHMs). Ultraluminous infrared galaxies (ULIRGs) comprise a population of galaxies that emit far-infrared (FIR) radiation with energies comparable to those of the most luminous quasars ($L_{\rm FIR} > 10^{12} L_\odot$; 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. OH masers are associated with star formation in the Galaxy, and ULIRGS mirror this trend (Darling & Giovanelli 2002), but with much larger maser linewidths. The most IR-luminous ULIRGS contain the OHMs, which is consistent with IR pumping of the OHMs (Darling 2007). Lo (2005) presents an excellent comprehensive review of these OHMs.

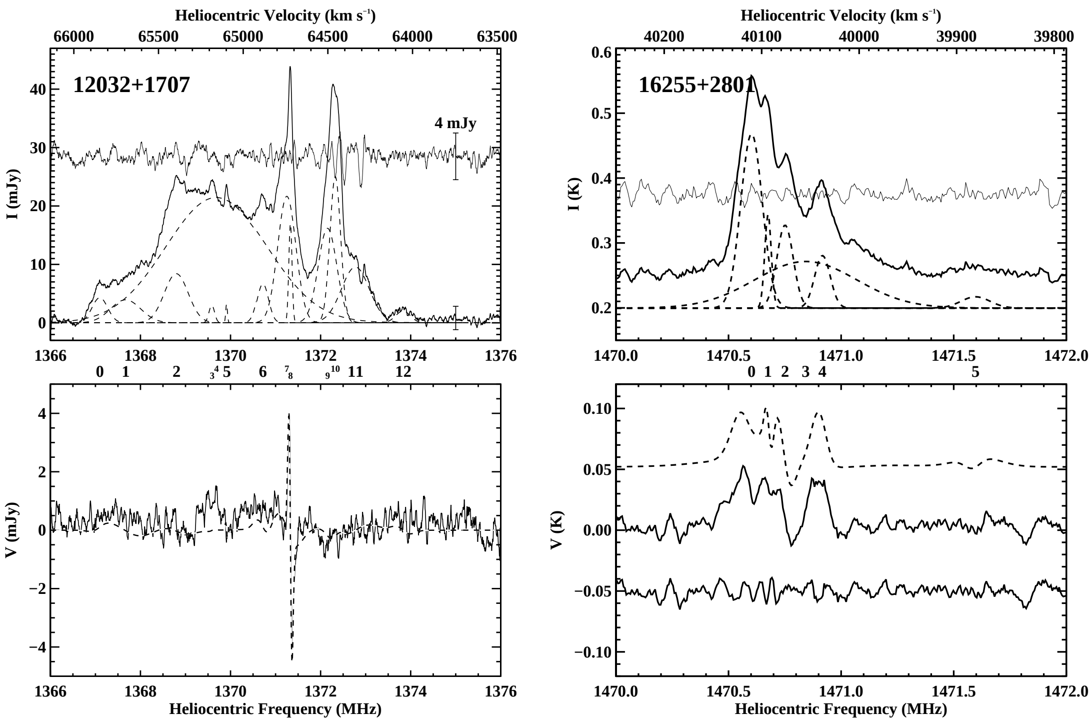

Fig. 1.— Circular polarization and Zeeman splitting for the OH Gigamaser 12032+1707 (left) and Megamaser 16255+2801 (right). Top, Stokes I, with dashed Gaussian components as numbered in between the two panels. Bottom, Stokes V with the dashed line fit being the best Zeeman-splitting fit. In both panels, the noisy signal-free lines plot the residuals between the data and fits.

When viewed by a single dish, a ULIRG typically shows many discernible OHM components on top of a much broader and stronger line. The broad component has linewidth ranging from ~ 100 to $\gtrsim 1000$ km s^{-1}; the multiple narrow components have linewidths ~ 30 to several hundred km s^{-1}. The broader line is probably the superposition of a large number of weak, individually indiscernible masers that form a roughly Gaussian-shaped line via the central limit theorem. VLBI maps of nearby OHMs, such as Arp 220 and III Zw 35, show that the single dish spectra resolve into many individual maser spots in the inner $\sim$100 pc (Rovilos et al. 2003, Pihlström et al. 2005).

How about the magnetic fields in these OHMs—are they strong, like those in the Galaxy's OH masers? To investigate this question, we performed a small survey of 8 OHM-containing ULIRGs using the Arecibo and Green Bank telescopes and found easily-detectable fields in 5 of them (Robishaw et al. 2008). Figure 1 shows the original survey's strongest field strength (for 12032+1707, Gaussian component 8) with line-of-sight field $B_{||} = 17.9 \pm 0.9$ mG, together with the current (ongoing) large survey's strongest field (for 16255+2802, Gaussian component 3) with total field. $B_{tot} = -18.4 \pm 5.5$ mG; we may find stronger fields as we progress with the rest of the survey. The field strengths are indeed comparable to those in Galactic OH masers, namely in the several milliGauss range or more. Often, the fields are so strong that Stokes V, which reveals Zeeman splitting, has high signal/noise and the fields are easy to measure, as in the bottom panels of Figure 1.

Measuring magnetic fields in OHMs provides information on several distinguishable fronts:

1. OHM Zeeman splitting measures the magnetic field strength and direction on the small scales of the OHMs themselves, which provides information on how the star formation process and magnetic forces interact. Thus far, with our meager sample of 8, we find rough similarity between field strengths in ULIRG OHMs and Galactic OH masers. This suggests that, within a cloud that has condensed enough to begin star formation, the *local* process of massive star formation occurs under relatively similar conditions even in galaxies with vastly different large-scale environments. This result has clear implications for the universality of star formation in galaxies, so it is important to build up better statistics on the magnetic field properties of ULIRGs.

2. The maximum field strength that can occur in OHMs establishes the dominance of magnetic pressure. In the Milky Way, just a few short years ago the maximum known field strength in OH masers was $B_{tot} \sim 10$ mG. However, Slysh & Migenes (2006) discovered much higher field strengths, $B_{tot} \sim 40$ mG in W75 N, which were confirmed by Fish & Reid (2007). The corresponding magnetic pressures are enormous: $\frac{P_{mag}}{k} \sim 10^{11}$ cm^{-3} K! Volume densities in OH masers cannot exceed $\sim 10^7$ without quenching the maser process (Reid, Myers, & Bieging 1987), so it is clear that magnetic pressure vastly exceeds thermal gas pressure.

3. OHM Zeeman splitting also tells the direction of the large-scale field in the regions where the OHMs reside, just as in the Galaxy. Many of these interacting ULIRG 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.

   For example, Figure 2 exhibits the situation for III Zw 35 as VLBI-mapped and modeled by Pihlström et al. (2001). The model, shown on the left, is an inclined 40-pc diameter ring rotating at 65 km s^{-1}. This velocity difference exceeds the line width, as shown in the middle panel, so velocity reliably separates the top and bottom of the ring. The magnetic field directions that we have detected (not shown here) *reverse with velocity*, and therefore from top to bottom—just like the velocities. This shows that the field lines are circumferential around the disk.

   This ringlike morphology is not universal. In the starburst galaxy M82, Jones (2000, 2006) finds a polar field in the nucleus and a more normal toroidal field in the disk, which suggests either that the field has been shaped by the galactic wind or that it has evolved because of a dynamo.

4. The left and right panels of Figure 1 reveal two fundamentally different types of field structure. For 12037+1707 on the left panels, the field is strong—but only in one single maser component.

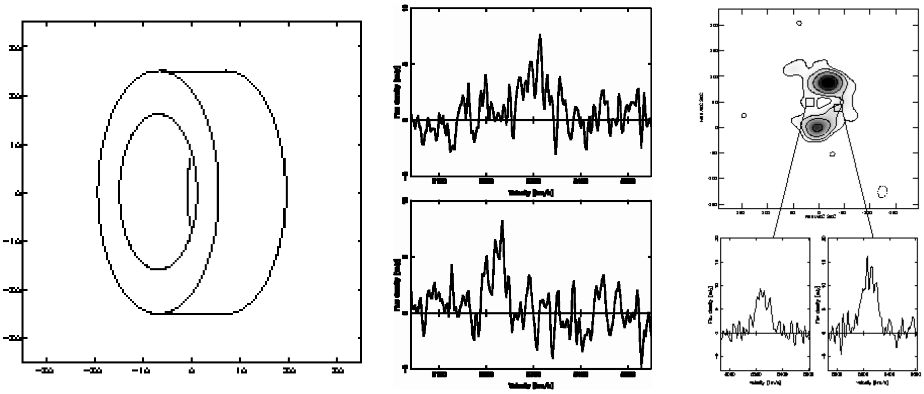

Fig. 2.— Right top, $\sim$ 30 milliarcsec resolution map from the MERLIN+EVN array of III Zw 35 from Pihlström et al. (2001). The left panel shows the model, which is an annulus inclined at $60°$ with inner radius of 16 and 25 pc rotating at 65 km s^{-1}. Profiles in the middle panel are the OHMs on the top and bottom of the rotating ring. The right panel maps the OHM intensity and shows profiles in the region having no relative Doppler shift. In this ULIRG, velocity reliably separates the top and bottom of the ring.

In contrast, for 16255+2801 on the right panels, the field permeates *all* maser components; not all are as strong as -18.4 mG, but they are all quite strong and they all have the *same direction*. This, in turn, is in contrast to sources such as III Zw 35 (see item 3 above), where the field *reverses* across the assembly of broad maser lines.

5. Interpreting the large-scale fields in terms of the large-scale dynamics requires knowing in which parts of the interacting region the OHMs are located. As we see from the example of III Zw 35 in Figure 2, this can be gleaned to some extent from single-dish spectra because the interacting regions often contain large velocity gradients, so the typical velocity is associated with a typical localized portion of the interacting region. This works fairly well for III Zw 35 because the velocity differences exceed the dispersions. This is not always the case. While we expect the survey information to be useful as a statistical indicator, the only *sure* way to establish these connections in individual cases is with VLB maps of the OHMs and their magnetic fields, so that individual field detections can be pinpointed on the map to reveal clear, unambiguous associations.

6. Consider now the large-scale *global* field strength in ULIRGs. The strong synchrotron radiation suggests the global field to be very high, in the mG range. For example, for the observed radio continuum fluxes from Arp 220 and other ULIRGs, minimum energy arguments suggest characteristic field strengths $\sim 1\,$mG (e.g., Condon et al. 1991; Thompson et al. 2006), or even more if one includes a proton component to the cosmic rays. If the field is significantly smaller than this, then inverse Compton losses would exceed synchrotron losses for cosmic-ray electrons by a large factor, making it energetically difficult to explain the observed radio emission. On the other hand, the minimum energy estimate may not apply in ULIRGs (Thompson et al. 2006), in which case the field could approach $\sim$ 10 mG; this is the value obtained for equipartition between the magnetic and total pressure as revealed by the gas surface density, as occurs in the Galaxy.

   Our current sample of ULIRG observations don't suggest such high global, ambient field strengths. Some of our ULIRGS exhibit linear polarization, either in the continuum, the

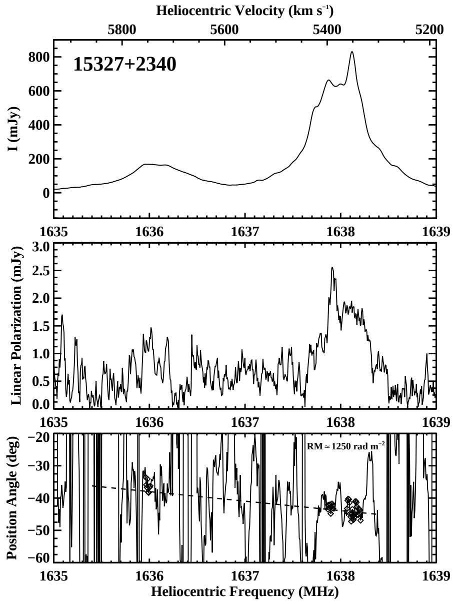

Fig. 3.— Linear polarization of IRAS 15327+2340 (Arp 220). Top, Stokes I; middle, linearly polarized intensity; bottom, position angle. The bottom panel also shows the fitted Faraday rotation as a dashed line whose slope was determined by fitting to the points marked as diamonds. All spectra are plotted as a function of heliocentric frequency (*bottom axis*). The top panels show the optical heliocentric velocity (*top axis*). All spectra are smoothed by a boxcar of 23 channels.

OHM line, or both. For example, Figure 3 shows our results for Arp 220. The top panel shows the Stokes I profile; the two bumps are the two hyperfine components commonly known as the 1665 and 1667 MHz lines, so they come from identical maser spots. The middle panel shows the linear polarization intensity, which peaks at about 2 mJy ($\sim 0.2\%$); this is small, but very well-detected.

What's really interesting is the bottom panel, which shows the position angle of linear polarization together with the dashed-line best fit, which provides Rotation Measure $RM \sim 1250$ radians m^{-2}. While this seems large, it is nevertheless *much* smaller than we anticipate from the mG-strength fields estimated above. Electron densities are ~ 1 cm^{-3} in the hot ionized gas, both from observations of X-ray emission (e.g., Grimes et al. 2005) and from theoretical models of supernova-driven galactic winds (e.g., Chevalier & Clegg 1985). Over a path length ~ 100 pc in the central portions of ULIRGs, this provides $\langle n_e B_{||} L \rangle \sim 0.1$ G cm^{-3} pc, or $RM \sim 80000$ radian m^{-2}. This is *60 times greater than we observe* and would produce a very easily-detected angle change exceeding 100 degrees over the line width.

Our smaller-than-anticipated RM might occur if the magnetic field fluctuates, either across the face of the maser emitting region or along the path length to the maser in the central regions. The interpretation of these data is thus currently difficult. Observations of more systems would be most helpful and may provide strong constraints on the thermal electron density or magnetic field structure (e.g., reversals) in the nuclei of ULIRGs.

7. The relative contribution of star formation and AGNs to the bolometric luminosity of local ULIRGs remains uncertain (Tacconi et al. 2002). We can help resolve this uncertainty by

determining whether the magnetic field properties of ULIRGs suspected to host bolometrically important AGNs (on the basis of, e.g., X-ray properties or IR colors) differ from those that appear to be dominated by star formation. This would represent an extension of Darling's (2007) conclusion that the very existence of OHMs requires the brightest ULIRGs.

3. INSTRUMENTATION

Current direct, in situ measurements of magnetic fields in active galaxies using Arecibo and the GBT show that magnetic fields are—as usual—at the core of star formation, energetic processes, and gas dynamics at scales large and small. Future observations will push to higher redshifts, and will need the ultimate point-source sensitivity. This mandates, at the present time, Arecibo, which has by far the best sensitivity in the world. Ultimately we will have the Square Kilometer Array, which will be required to push past $z \sim 0.7$—which is where we should begin to see unambiguous cosmological evolution of field strengths.

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