First Measurements of the Zeeman Effect in CH

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This proposal is a request to use the Arecibo telescope in astronomy's first attempt to measure the Zeeman effect in the 700 MHz lines of CH. Detection of the Zeeman effect in these lines would give unprecedented magnetic field information about star-forming gas at densities as high as 10^6 cm^{-3}. Currently, astronomers have embarrassingly little information on the field strength in molecular gas with densities $10^5 < n < 2\times10^6$ cm^{-3}, which leaves theories of star formation unconstrained by observations in that most critical density window.

Over the past ten years, magnetic fields have become an increasingly popular ingredient in recipes for star formation in molecular clouds. Unfortunately, after more than thirty years of Zeeman observations, the number of star-forming regions with even a single field strength measured via *detection* of the Zeeman effect in non-masing molecular lines stands only at fifteen. This is not for lack of trying (see Crutcher 1999). Many hundreds of hours of telescope time have been devoted to Zeeman experiments, and only about 10% of that time has resulted in any kind of detection. Worse yet, it is fair to say that virtually all of the regions likely to give detections in the standard Zeeman tracers, HI and OH, have already been observed with the largest telescopes available today.

The only *molecule* that has been used extensively in Zeeman searches to date is OH. The $^2\Pi_{3/2}$ $J = 3/2$ OH transitions at 1665 and 1667 MHz produce Zeeman splitting that can be detected in emission lines (T_A ~a few K) with Arecibo in tens of hours of integration, or in absorption lines seen against bright background sources (T_A ~ tens of K) in tens of minutes (Goodman et al. 1989; Crutcher and Troland 2000). These lines tend to sample gas with densities around 10^3 to 10^4 cm^{-3}. These densities correspond to the "envelope" regions around dense, star-forming cores, but are not high enough to probe the core gas itself.

At higher densitities, Güsten et al. (1994) used Effelsberg to measure the Zeeman effect in the previously unused high-lying $^2\Pi_{3/2}$ $J = 7/2$ transition of OH to sample 100 K gas with n~10^6 cm^{-3}, and tens of hours were required for their single detection of 3100 μG in W3 OH . Crutcher and collaborators (Crutcher et al. 1999) used the 3 mm lines of CN to measure the Zeeman effect with the 30-m telescope in a few massive star-forming regions with densities ~10^3 to 10^6 cm^{-3} and T~50 K. As was the case with the high-lying OH transition, the CN observations required tens of hours of integration per detection (of $B_{||}$ ~300-700 μG). In this proposal, we seek to detect fields in high-density (~10^6 cm^{-3}) gas by observing CH at Arecibo, using far less telescope time.

Arecibo was used for the first detection of the 700 MHz lines of CH, in 1983 (see Ziurys and Turner 1985). The transitions observed at 702 and 725 MHz are analogous to the 1667 and 1665 MHz lines of OH (see Table 1), and should have the same Landé g-factor as those transitions. Unlike OH, however, these lines represent a "first excited" level in CH, rather than a ground state. Ziurys and Turner estimate that the 700 MHz CH transitions, which they see only in absorption, are excited in regions with density ~10^6 cm^{-3}.

Table 1: Comparable OH and CH Transition Frequencies

Hyperfine Transition	OH Frequecncy [MHz]	CH Frequency [MHz]
$^2\Pi_{3/2}$ $J = 3/2$ $F = 1-2$	1612.2310	722.303[1]
$^2\Pi_{3/2}$ $J = 3/2$ $F = 1-1$	1665.4018	724.788[2]
$^2\Pi_{3/2}$ $J = 3/2$ $F = 2-2$	1667.3590	701.677[2]
$^2\Pi_{3/2}$ $J = 3/2$ $F = 2-1$	1720.5300	704.175[1]

Assuming Ziurys and Turner are right and the density probed by these CH transitions is ~10^6 cm^{-3}, equilibrium models and empirical evidence suggest that the magnetic field in the absorbing gas should be hundreds to thousands of μG (Myers and Goodman 1988; Crutcher 1999). While it is true that even Arecibo's

[1] Detected at Arecibo (Turner 1988).
[2] Detected at Arecibo ((Ziurys and Turner 1986).

spatial resolution at 700 MHz is coarse (7'), the regions giving rise to CH absorption fill a small fraction of the beam, and the proposed measurements *will* be legitimately representative of small clumps of high-density gas.

If our CH Zeeman experiments are successful, the data acquired under this program, and its future descendants will provide a database of field strengths substantial enough to allow a "statistical" understanding of the magnetic field in massive star-forming regions--something which has not been possible to date.

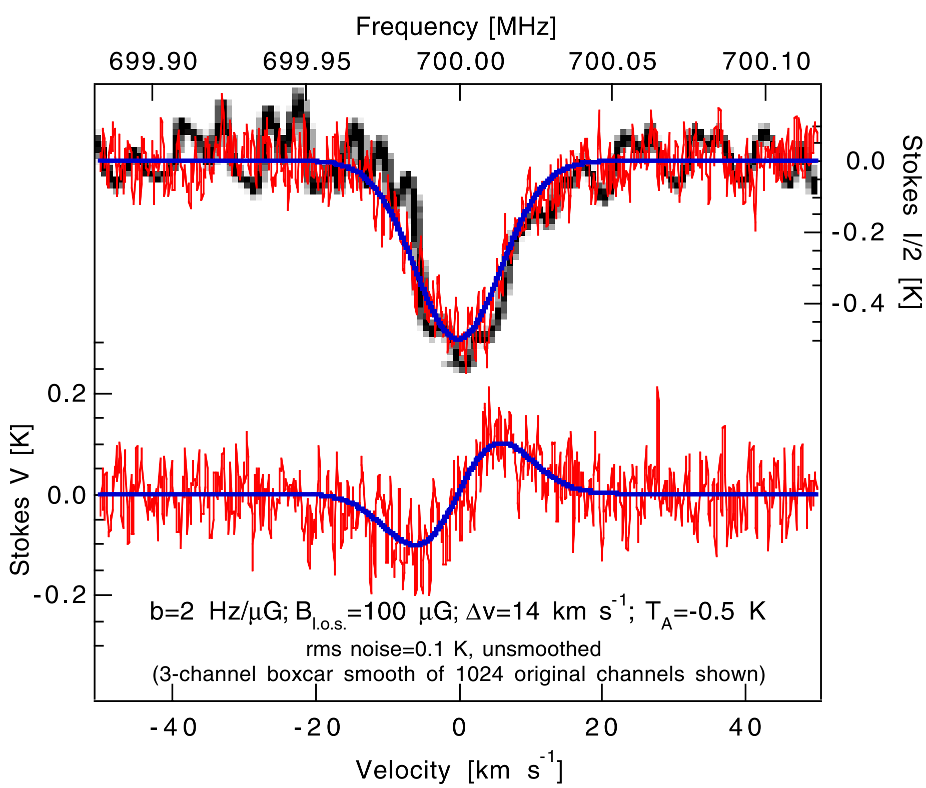
Technical Discussion and Time Request

Even when the field is as high as 1000 μG, the Zeeman splitting of the CH lines (like all the other thermally excited lines observed to date) will still be much less than a typical Doppler line width in a massive star-forming region, Δv~10 km s^{-1}. However, the split components of the lines are oppositely circularly polarized, so we can still measure the Zeeman effect, by creating a Stokes-*V* (RCP-LCP) spectrum. The "Zeeman profile" in the Stokes-*V* spectrum will look like the derivative of the line, and is described by the expression

$$V = \frac{d\left(\frac{I_R + I_L}{2}\right)}{d\nu} bB\cos\theta$$

where *b* is a "splitting factor" proportional to the Landé g-factor, *B* is the magnetic field strength, and θ is the angle of the field to the line of sight. The *b* factors should be 1.96 and 3.27 Hz/μG for the 701.7 and 724.8 MHz lines, respectively[3].

If the 700 MHz CH transitions indeed arise in regions with ~1000 μG field strengths, and there is nothing unusual about the CH *b*-factors, *we should be able to measure the Zeeman effect in a massive star-forming region less than one hour*. The Figure shows the expected Zeeman profile for CH under the conditions labeled



on the graph. At Arecibo, in a 2-hour integration, the rms noise level at 700 MHz should be about 0.2 K, assuming 3 km s^{-1} channels and that the H II region's continuum raises T_{sys} to 700 K. The Stokes I/2 line parameters (width of 14 km s^{-1} and amplitude of -0.5 K) in the Figure are representative of a real H II region. In fact, the blurry spectrum in the background is the actual 725 MHz Arecibo spectrum for W51 published in Ziurys and Turner (1985). The Stokes-*V* profile in the figure is shown for very pessimistic assumptions about the field (only 100 μG), and higher-than-planned spectral resolution (for illustrative purposes).

The important quantity to consider to evaluate the feasibilty of our proposal is the ratio of the expected Zeeman signal (~0.1 K for 100 μG as in the Figure or 1 K for 1000 μG) to the rms noise (~0.2 K/per-2-hour track, assuming an effective T_{sys} of 700 K and smoothing to 3 km s^{-1}*). For example, a 1000 μG field in a W51-like source could be detected at 3σ in less than an hour.* Sources with similar fields but narrower lines, and/or lower continuum contribution to the effective system temperature could be detected even faster. Of course, it is also true that weaker fields and noisier sources will take longer to detect. Our plan is to abandon any source not giving a detection in two full tracks (~4 hours) of observation, and call that measurement an upper limit.

Technical Requirements: As stated on the cover sheet, we have discussed the feasibility of this project with respect to both RFI and antenna/receiver/backend issues, with Edgar Castro. We will need two new filters for this experiment, one centered around each CH line shown in the box in Table 1. The filters should be as narrow as is feasible. As of January 2000, the Arecibo RFI and broadcast lists still show our two frequencies as "clear." In addition to the the new filters, we expect some physical modifications may need to be made to the relevant antenna for 700 MHz dual-polarization observations. We will be happy to consult on these purchases and modifications as needed.

The cross-correlation technique we plan to use (see Heiles 1999) to derive the Zeeman signal requires that we determine polarization phase by tracking two linearly polarized sources as they transit (see below).

Source List and Time Request: We will begin our search for a detection of the CH Zeeman effect with the W51 position observed by Ziruys and Turner (1985). After that, we will turn our attention to NGC2264 and the "other six sources" that gave CH detections mentioned in Turner 1988. We are counting on Barry Turner and Lucy Zirurys to provide us with the (unpublished) list of exactly which H II regions near the Galactic plane those six sources are, and hopefully with a spectrum for each, in advance of our experiment. In addition to the H II regions, almost all of which are likely toward the inner Galaxy and in the plane, we will need to time to measure polarization for a full (two-hour) track for each of two calibrator sources whose declinations are close to the latitude of Arecibo. The memorandum AOTM 99-01 by C. Heiles (on-line at www.naic.edu) lists several such sources, at a variety of R.A.'s, so that part of our time need not be scheduled around 19^h R.A. We expect that **40 hours of total time** will realistically give us 4 hours (two-tracks) on each of 8 H II regions, plus 4 hours for calibration observations, and 4 hours for setup experiments. Lastly, we note that one of us (C.H.) will be at Arecibo for 3 three-week intervals in September, October, and November of 2000, and scheduling this proposal in those time periods would be most efficient for us.

References

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[3] These b-factors, calculated and tabulated in Heiles et al. 1993, assume that CH has no unusual magnetic properties. Quantum chemistry experts have assured us that CH should not be unusual, but no laboratory measurements exist for confirmation of the "expert" opinions. Our astrophysical measurements may ultimately serve as that confirmation.