MASERS AND STELLAR MAGNETIC FIELDS

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ABSTRACT. Observations of circular polarization of molecular masers associated with late type giant and supergiant stars can be used to estimate the magnetic field strength in the masing region. Magnetic field strengths of $\sim$ 5 mG are deduced for OH masers in circumstellar envelopes at distances of $\sim 10^{16}$ cm from the star, and magnetic field strengths of $\sim$ 50 G are deduced for SiO masers that reside above the photosphere. Extrapolation to the stellar photosphere suggests that average surface magnetic fields are on the order of 10^3 G.

1. Introduction

Magnetic fields have been detected in only a few classes of stars. The most detailed measurements, of course, are for the Sun—a G2V star which has localized regions of $\sim 10^3$ G fields that cover about 1% of the surface. Late G– and K–type dwarf stars have magnetic fields of strength comparable to the Sun, but with surface coverages of about 50% (Marcy 1984). The strongest magnetic fields are $10^3 \rightarrow 10^4$ G, measured for stars of spectral type Ap and Bp (*e.g.,* Borra *et al.* 1982). Indirect indications of stellar magnetic fields can be found for dMe and RS CVn stars, where cyclotron and other non-thermal emission mechanisms that require magnetic fields are thought to operate.

Stellar magnetic fields can be directly measured by observations of the Zeeman effect in spectral lines. If the magnetic field is large enough to split the Zeeman components by more than a line width, one can deduce a magnetic field strength. If the splitting is less than the line width, a detection of the characteristic "S-shaped" spectral signature in circular polarization yields an estimate of the *longitudinal component* of the magnetic field. Molecular material in the expanding envelopes of late-type giant and supergiant stars is observed to exhibit maser action (*e.g.,* Reid and Moran 1981). The molecular species known to mase include OH (hydroxyl), H_2O, and SiO. The Zeeman effect has been detected for OH and SiO masers, and observers are attempting to detect the effect for H_2O masers.

2. Stellar Masers

Stellar masers are associated with (1) long period variable stars (usually Mira variables) with periods of $\sim$ 400 days and (2) M–type semi-regular variables and supergiants often with much longer periods. Copious emission and absorption lines are seen at optical and infrared wavelengths toward these cool stars (T$\sim$ 2000 K). Systems of absorption lines are found red- and blue-shifted with respect to the stellar velocity (Reid and Dickinson 1976); these lines are believed to originate in a dynamically complex region in or just above the

R. Beck et al. (eds.), Galactic and Intergalactic Magnetic Fields, 21–25.

stellar photosphere that contains outflowing and infalling material (*e.g.,* Willson and Hill 1979). Beyond this region, at a distance of $\sim$ 10 stellar radii, is a quasi-stationary region at a temperature of $\approx$ 800 K, which serves as a reservoir for infalling material as well as a site for the formation of dust grains (Hinkle *et al.* 1982). Once formed, the grains are accelerated by radiation pressure, they collide with gas-phase molecules, and the outwardly moving material forms an extended circumstellar envelope.

OH, H_2O, and SiO masers also are found toward these stars. The OH masers are in the ground-state and do not require high temperatures to excite the molecules. However, H_2O and SiO masers are from excited rotational-vibrational states that are 600 K (for the H_2O $6_{16} - 5_{23}$ transition) and 1800 K (for the SiO $v = 1, \Delta J = 1$ transitions) above the ground state. Thus, these species mase in regions closer to the stellar surface than the OH masers. The SiO maser emission appears to come from both the "stationary" region, at a radial distance of 10^{15} cm from the center of the star, and from the infalling material near the photosphere. H_2O maser emission might also occur in these regions as well as from the inner portions of the expanding circumstellar envelope. The double-peaked 1612 MHz OH maser emission originates at the greatest distance from the central star.

2.1 OH MASERS

The OH maser emission occurs in a thick shell and the most intense emission arises from caps on the front (approaching) and back (receding) sides of the envelope (Reid *et al.* 1977; Booth *et al.* 1981). The 1612 MHz OH maser emission typically comes from radial distances from the central star (R_{maser}) of 8×10^{15} cm for Mira variables and 5×10^{16} cm for the supergiants and optically unidentified stars (Schultz *et al.* 1978).

For magnetic fields greater than about 1 mG, the Zeeman splitting is greater than the maser line-width and oppositely polarized σ−components can be directly observed. Measurement of the frequency difference between σ−components can, in principle, determine a magnetic field strength, B_{maser} , in the masing region. However, the 1612 MHz OH masers are usually only slightly polarized since (1) they are formed at great distances from the central star in regions of the low magnetic field strength and (2) the 1612 MHz masers have a large number of components and spectral overlap of oppositely polarized components may significantly reduce the observed polarization. Indeed, when observed with high spectral resolution (*e.g.,* 100 Hz), supergiant 1612 MHz masers show more polarization than when observed at lower resolution, suggesting $B_{maser} \sim 2$ mG (Cohen *et al.* 1987). In two stars (U Ori and IRC+10420) strong circular polarization has been detected, indicating B_{maser} values of up to 10 mG (Reid *et al.* 1979).

2.2 SiO MASERS

SiO masers are seen predominantly in excited vibrational levels, with the strongest masers in the $v = 1$ state. Since even this lowest excited vibrational state is about 1800 K above the ground state, SiO masers are likely to originate close to the central star. VLBI maps by Moran *et al.* (1979) indicate a spread in the maser spots, and hence an estimate for R_{maser} , of $\sim 10^{14}$ cm for R Cas (a Mira) and $\sim 10^{15}$ cm for VX Sgr (a supergiant).

Barvainis, McIntosh and Predmore (1987) detected circular polarization from three Mira variables (R Leo, W Hya, and R Cas) and two supergiants (VY CMa and VX Sgr). Unlike the OH masers in which mG fields split the lines by more than the line width, the Zeeman splitting for SiO is less than a line width for fields less than $\sim 10^3$ G. In this case the amplitude of the "S-shaped" Stokes–V spectrum is used to estimate the *longitudinal* component of the magnetic field. Assuming a magnetic field direction 45° from the line of sight, values of $B_{maser} \approx 30$ G for the Mira variables and ≈ 70 G for the supergiants are estimated.

2.3 H_2O MASERS

There are no published detections of circular polarization of H_2O masers (Barvainis and Deguchi 1989, Moran *private communication*). Upper limits for magnetic field strengths are 5 and 0.5 G in the maser region for Mira variables and supergiants, respectively. The radial distance of the H_2O maser region is not well determined, but probably lies between the SiO and OH maser regions at $\sim 10^{15}$ cm from the star.

3. Stellar Magnetic Field

The average magnetic field at the surface of the star, B_* , can be extrapolated from the field measured in the masing region inward to the stellar radius, R_* . Assuming the field strength varies as a power of the distance from the star with some exponent, α, then

$$B_* = B_{maser}\left(\frac{R_{maser}}{R_*}\right)^{\alpha} \quad (1).$$

Because the radial structure of the magnetic field in the circumstellar envelope is not known, the exponent α is uncertain and stellar fields deduced from Eq. (1) are only order-of-magnitude estimates. Reid *et al.* (1979) first proposed the use of Eq. (1) to estimate surface magnetic field strengths from maser data. They assumed $\alpha = 2$ and Zeeman splitting measurements of OH maser lines to estimate surface magnetic fields of $\sim 10^2$ and $\sim 10^3$ G for U Ori (a Mira) and IRC+10420 (an unusual F-type supergiant), respectively.

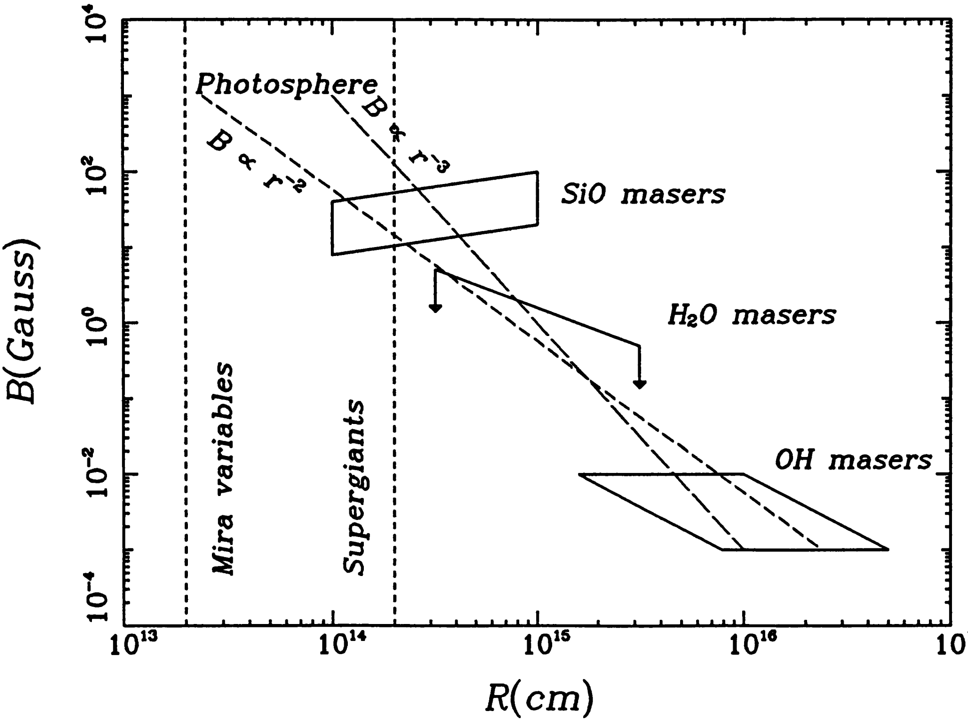

Figure 1. Magnetic field strength, B, as a function of distance, R, from the center of a star with circumstellar maser emission.

https://doi.org/10.1017/S0074180900189429 Published online by Cambridge University Press

Figure 1 displays a plot of the magnetic field strength, B, in the masing regions as a function of distance, R, from the center of the star. The range in the SiO and OH maser data are indicated schematically by quadrilaterals for each masing species. The H_2O maser results are upper limits. While we have mixed data for all stellar masers, in general, Mira variables have R values that lie at the lower end of the plotted ranges, while supergiant values lie at the upper end of the plotted ranges. We have also indicated ranges of stellar photospheric radii by the vertical dashed lines, noting that Mira variables tend to be smaller than supergiants. The sloping dashed lines indicate possible power law exponents (α). The recent measurements of circular polarization of SiO masers indicate that α is between 2 and 3 and greatly improves the accuracy of the extrapolated surface magnetic field strengths. We conclude that Mira variables and supergiants with circumstellar maser emission have mean surface magnetic field strengths on the order of 10^3 G.

4. Closing Comments

While giant and supergiant stars with circumstellar maser emission are of late spectral type (M–type), there is one example of an F–type supergiant with maser emission, IRC+10420. Perhaps IRC+10420 has a fossil circumstellar shell from an earlier M–type phase (Mutel *et al.* 1979). Thus, we now have magnetic field measurements for a wide range of types of stars including some red giants and supergiants, the Ap/Bp magnetic stars, the Sun, and some late G– and K–type dwarf stars. It is interesting to note that all of these types of stars, whether hot or cool or giant or dwarf, seem to have kilo-Gauss fields that cover a portion of the stellar photosphere. Whether this is an observationally selected result (since stellar magnetic fields less than 100 G are difficult to detect) or has some physical significance remains to be determined.

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PARKER: I suspect that the general 10^3 G that you find for most stars represents approximate equality between $B^2/8\pi$ and the photospheric gas pressure which brings me to my question. Inward extrapolation of your magnetic field measurements suggests 10^4-10^5 G at the photosphere. That would be truly amazing, and one would feel compelled to extrapolate farther inward to more substantial material densities. I am fascinated by the possibility of such intense fields.

REID: The plot of magnetic field strength versus distance from the center of the star gives the extreme ranges of parameters from a variety of stars, including giants and supergiants. The supergiants generally have larger magnetic fields, but correspondingly larger physical dimensions, so their photospheric fields are not likely to be as high as you extrapolate.

SPANGLER: Your results indicate fields of about 10^3 G in all objects. Such fields must be highly inhomogeneous, or chosen by selection effects, since the fields inferred from nonthermal radiation of RS CVn stars are considerably lower, say 10-100 G.

REID: Certainly stellar magnetic fields are only detected if they are greater than 10 to 100 G, and many stars fall below these limits. However, the observations of the Sun and of K stars suggest that, in stars with disk averaged fields less than $\sim 10^2$ G, local fields can still exceed 10^3 G but with low filling factors.

RUZMAIKIN: What can you say about convection and rotation in supergiant stars to generate these magnetic fields?

REID: Optical evidence suggests a small number of very large convective cells and slow rotation in Mira variables. Observations of OH masers do not find significant evidence for rotation (i.e. rotation speeds $\lesssim$ 10 km/s in the expanding circumstellar envelope). The possibility of detecting both convective and rotating motion is best for SiO masers using the VLBA.

PISMIS: I like to ask you about the lifetime of the masers (H_2O, OH) within the extended atmosphere of the giant stars and of magnetic phenomena associated with them. My interest stems from the fact that planetary nebulae are believed to originate from the detachment of the extended atmosphere of evolved giant stars. Would planetaries still show masers if they have ages of, say, 10^4 years?

REID: Stars with SiO, H_2O, and OH masers may be precursors to planetary nebulae. However, to my knowledge no planetaries have associated maser emission. Possibly the conditions required for maser activity do not exist in the planetary phase.

FEDORENKO: There exists an interesting relationship between your results on the magnetic fields at $r \sim 10^{16}$ cm from the red giants, namely fields $B \sim 100$ G are just what is required in the models of the radio supernovae, exploding into the circumstellar cavities.