Magnetic Field on Late-Type Stars

J.R. Shi & G. Zhao

(*National Astronomical Observatories, Chinese Academy of Sciences, Beijing* 100012)
E-mail: sjr@yac.bao.ac.cn

Abstract We reviewed the magnetic field measurements on late-type stars, and discussed the correlation between the X-ray emission and the magnetic fields. We found that the F_X or L_X/L_{bol} correlate fairly well with magnetic flux. We also found a clear correlation between the high-temperature components and the magnetic field strength.

The magnetic field is very often a crucial parameter in astrophysical problems. It plays a key role basically everywhere in the Universe, at all time and spatial scale. In the case of stars, the magnetic fields affect their formation, evolution, stellar activity and the late stage of their lives.

Ever since Robinson's (1980), measurements of magnetic field strength B, and surface filling factor of magnetic region, f, on late-type stars have been made by several investigations. Our knowledge of both the intensity and structure of the magnetic field of late-type stars has been considerably improved.

1 Measurements of stellar Magnetic Fields

Virtually all measurements of stellar magnetic fields make use of the Zeeman effect. Typically, one of two general aspects of the Zeeman effect is utilized: (1) Zeeman broadening of magnetically sensitive lines, or (2) circular polarization of magnetically sensitive lines (Zeeman Doppler Imaging).

1.1 Zeeman Broadening

In normal Zeeman effect, a spectral line splits into three components: two σ components on either side of the nominal line center and one unshifted π component. The wavelength shift of a given σ component is $\Delta\lambda = k\lambda^2 gB$, where k is a constant, g is Landé g-factor of the specific transition, B is the strength of the magnetic field, and λ is the wavelength of the transition. Note this shift is λ^2-dependent, which means that the infrared observations are generally more sensitive to the magnetic fields than optical observations.

Robinson et al. (1980) pioneered a very successful technique to measure the Zeeman broadening of optical and near-infrared lines by comparing the two or more line profiles that cover a range in magnetic sensitivity. However, no "ideal" pairs (i.e. clean lines identical in all respects except their Landé factors) are available, and large magnetic flux (fB) were recorded for stars with widely different rotation rates and activity levels. Clearly, a refined analysis including treatment of radiative effects in the Zeeman components themselves is needed.

Saar and co-workers (Saar & Linsky 1986 and Saar 1988) developed the method further and used it to measure the magnetic field strengths and filling factor in the active regions of many stars, by assuming either a two-component atmosphere $F_{\rm obs} = fF_{\rm mag}(B) + (1-f)F_{\rm quiet}(B=0)$ or a three-component atmosphere (including star spots), where F refers to the radiative flux observed from the magnetic or quiet components of the atmosphere.

Fig. 1 shows the spectra of EV Lac and the inactive comparison star GJ 725B. The presence of Zeeman split σ components is clear on either side of the magnetic sensitive Fe I ($g = 2.5$) line at 8468.4 Å. Johns-Krull & Valenti (1996) determined $B = 3.8 \pm 0.5$ kG with $f = 0.50 \pm 0.15$ from the data.

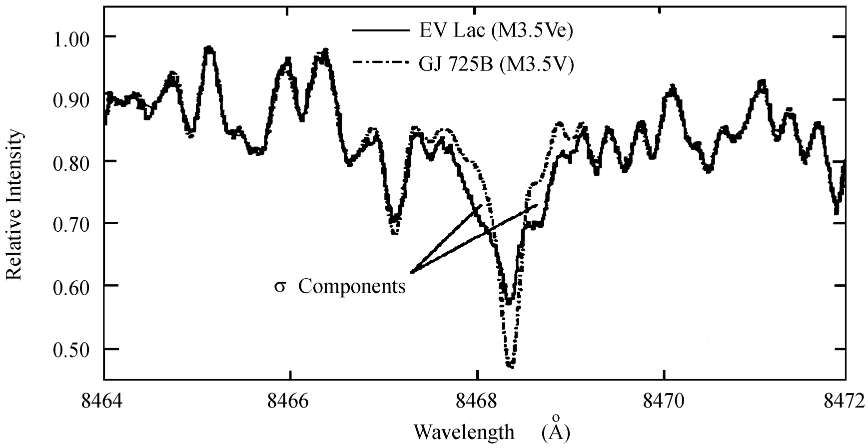

Fig. 1 Spectra of the flare star EV Lac and inactive star GJ 725B in the vicinity of the magnetically sensitive Fe I line at 8468.4 Å. Note that the spectrum of the inactive star matches the spectrum of EV LAC for all the nearby magnetically insensitive TiO lines, but fails to match the σ components on either side of the Fe I line, demonstrating the presence of magnetic field on the flare star. (From Johns-Krull & Valenti 2000)

The pre-main-sequence T Tauri stars are bright X-ray sources with the ratio of X-ray to bolometric ($L_X/L_{\rm bol}$) well above the level of saturated X-ray emission, $L_X/L_{\rm bol} > 10^{-3}$. It is believed that there are strong magnetic fields on these stars (Shu et al. 1997). Using high resolution infrared spectrum Johns-Krull & Valenti (2000) also derived the magnetic flux $fB = 2.4$ kG for naked T Tauri star Hubble 4.

The major drawback of the techniques is that they provide no information on the three-dimension (3-D) structure of the magnetic field across the stellar surface.

1.2 Zeeman Doppler Imaging (ZDI) of Rapid Rotators

Semel (1989) proposed to measure, in particular case of rapidly rotating late-type stars, the full profiles of magnetic Zeeman signatures in circular and (whenever possible) linear polarization. This technique can map the radial, meridional and azimuthal components of the magnetic field for rapidly rotating stars using profiles of some 2000 spectral lines in circularly polarized light (Donati & Brown 1997; Donati et al. 1997). This technique allows one to access the detailed topology of the stellar surface magnetic structure as well as its variation throughout a complete activity cycle. Donati & Cameron (1997) and Donati et al. (1999) have found that magnetic images of rapidly rotating cool stars are indeed extremely complex.

2 Magnetic Fields and X-ray Emission of Late-type Stars

The spread in the observed X-ray luminosity mainly reflects the efficiencies of stellar coronal heating, and the heating mechanism is mainly due to the interaction between stellar magnetic fields and coronal plasma. Linsky (1999a) concluded that the active phenomena for late-type stars result from the stressing of magnetic field by convective motions. So the obvious parameter related to stellar X-ray emission of late-type stars is the magnetic field.

2.1 X-ray Emission and the Magnetic Fields

Falconer et al. (2000) have found that the brighter the X-ray corona, the stronger the magnetic field in which it resides. They suggested that if the Sun had no magnetic field, it would have little or no X-ray corona. Saar (1996, 2000) found that X-ray emission correlate fairly well with fB, and the data showed a linear relationship. Here, we presented the relationship between the X-ray flux (F_X) or heating efficiency ($L_X/L_{\rm bol}$) and the magnetic flux in Fig. 2. For the single and wide binary stars, an excellent correlation between F_X or $L_X/L_{\rm bol}$ and magnetic flux can be seen. It seems that the coronal activity of late-type stars depends on the magnetic flux, namely both the magnetic field strength and the area of active region. For the binaries, the case is complex, maybe all the companion stars contribute a considerable emission to the total observed flux as independent components (Maggio et al. 1990), or the active phenomena in close binary stars are qualitatively different from phenomena on single stars (Linsky 1999b).

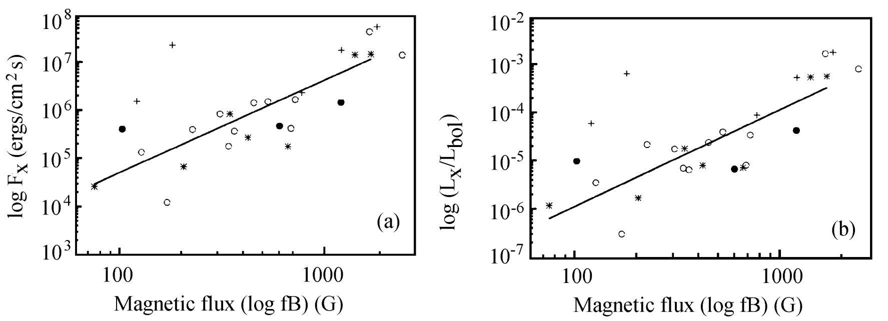

Fig. 2 The X-ray flux (F_X) and ratio of X-ray to bolometric (L_X/L_{bol}) versus the magnetic flux. **a** the X-ray flux to magnetic flux; **b** the L_X/L_{bol} to magnetic flux. The '**opened circle**','**filled circle**', '**asterisk**' and '**cross**' represent the single, binary, wide binary and RS CVn stars, respectively.

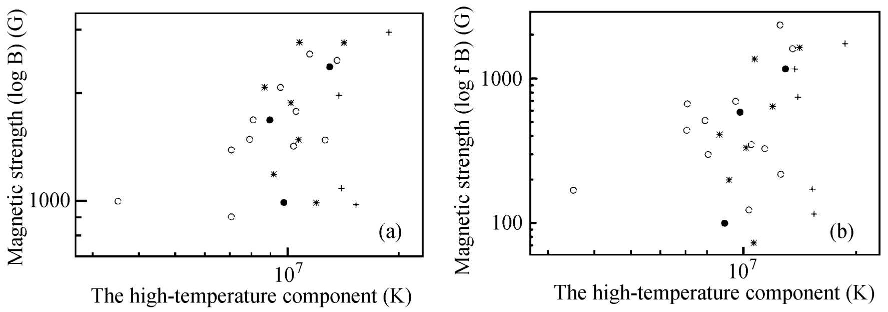

Fig. 3 The X-ray temperatures versus the magnetic fields. (a) the high-temperature component to magnetic field strength; (b) the high-temperature component to magnetic flux. For symbols see Fig. 2.

2.2 Coronal Temperature and Magnetic Fields

Mullan & Fleming (1996) suggested that the active corona is heated magnetically while the quiet corona may be heated acoustically. Shi et al. (1998) have used two-temperature models to fit the stellar X-ray spectrum (ROSAT) and found that the magnetic field strength of our program stars is correlated with the high-temperature component of the corona. Using the new magnetic field strength, Shi et al. (2002) confirmed this result, which is shown in Fig.3. For single stars, the correlation between the high-temperature component and the magnetic field strength is very clear, while no correlation for magnetic flux. This result suggests that the high-temperature component is related to the magnetic field strength at least for single stars.

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