Six Methods for Distinguishing Rotation and Reversal in a Stellar Magnetic Field

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Periodic changes in a stellar magnetic field can be explained in two ways: the oblique rotator model or the solar cycle model. Although many papers favor the oblique rotator model, there has not been enough evidence to rule out the solar cycle model definitively. This paper presents five new observations (together with an old one) that can be carried out to distinguish magnetic field rotation and magnetic field reversal.

Subject headings: stars: activity – stars: magnetic fields – stars: rotation
1. Introduction

Periodic changes in a stellar magnetic field can generally be explained in two ways: the oblique rotator model assumes that the magnetic field rotates, while the solar cycle model assumes that the magnetic field reverses. Although many papers favor the oblique rotator model, to date there has been no reason to discard the solar cycle model definitively. Babcock (1951, 1958) once discussed the advantages and disadvantages of these two models with respect to interpreting data from typical $\alpha$-variables. While the available data favored solar cycle (reversal) models, Babcock did not arrive at a definitive conclusion.

The intensity and polarity of a stellar magnetic field have traditionally been used to compare models, but these data provide only a limited view of the magnetic field behavior. If other types of data could be obtained, the choice of model would be more convincing.

This paper discusses five new methods and one old method of determining the reason for periodic changes in a stellar magnetic field. All the new methods make use of additional data such as the line-of-sight magnetic field, the transverse magnetic field, the polarization angle, and radio-pulse radiation. Used together, the true nature of a stellar magnetic field change can be ascertained correctly.

2. Six Methods for Distinguishing Rotation and Reversal in a Stellar Magnetic Field

2.1. Observing Polarity Changes in a Population

The first method has been used before. If the magnetic field is reversing, its polarity must change twice per cycle. If the magnetic field rotates, then its intensity must undulates periodically but its polarity may not reverse. The necessary conditions for observing a
polarity reversal are: 1) the magnetic inclination (the angle between the magnetic axis and the spin axis) is not equal to zero; 2) the spin inclination (between the spin axis and the line of sight) is not equal to zero; and 3) the sum of magnetic inclination and spin inclination is greater than 90 degrees. In other words, if the magnetic inclination and/or spin inclination is too small, the polarity will not appear to reverse. If all objects in a large sample exhibit polarity reversal, the oblique rotator model can be ruled out. Babcock (1958) used this method to analyze data on typical $\alpha$-variables, resulting in forceful support for the reversal model.

Although the later statistics (Borra et al. 1982) indicated that only approximately two-thirds of Ap/Bp stars with periodically varying magnetic field measurements are known to exhibit polarity reversal, the difference between this result and Babcock’s may come from the illegibility of weak signals. In order to have a strong persuasion, the samples with blurrier data should first be removed and then only the reliable data be used as evidences. If all the samples with good periodicity and high signal-noise ratio exhibit polarity reversal, especially, if they all exhibit a fair degree of symmetry about the $H = 0$ axis in their reversals, it is sure that the model of magnetic field reversal is correct.

### 2.2. Phase Relationship of Two Field Components

The second method compares the line-of-sight and transverse magnetic field phases. When a magnetic field reverses, the two components should change at the same time. If the magnetic field is rotating, however, there will be a 90 degree phase difference between the two components. This can be observed through the Zeeman Effect: the magnetic field both splits and polarizes spectral lines. The line-of-sight magnetic field will induce circular polarization in the spectral line, while the transverse magnetic field will induce linear polarization. The two components of the magnetic field can be determined simultaneously
by measuring changes in the line width. As shown in the lower panel of Fig. 11, it is obvious if the two components are in phase; in this case the reversal model must be selected. If the phase difference of the two curves is about 90 degrees, as shown in the upper panel of Fig. 11, the oblique rotator model is more appropriate.

### 2.3. Relationship between Polarization Angle and Magnetic Field Intensity

The transverse magnetic field can cause Zeeman splitting, in which case the wings of a spectral line are mainly composed of linearly polarized light. The polarization angle of the spectral line can also help determine whether the magnetic field rotates or reverses. If the magnetic field is rotating, its polarization angle will swing back and forth between two values. If the magnetic field reverses, its polarization angle will be fixed. Note that in both situations, Faraday rotation has been ignored.

If we consider Faraday rotation, then magnetic field reversal can also induce periodic changes in the polarization angle. This oscillation is driven by changes in the magnetic field intensity. At the moment corresponding to the polarization angle’s middle value (halfway between its extrema), the intensity of the line-of-sight magnetic field should reach its maximum under the rotation model. If the intensity of the line-of-sight magnetic field instead reached its minimum value, the magnetic field must have reversed. In fact, this method is based on the same principle as that described in Section 2.2. The only difference is that the intensity of the transverse magnetic field is inferred from the polarization rather than being measured directly.
2.4. Phase Relationship between Radio Pulses and the Magnetic Field

Pulsed radiation was once considered a unique behavior of neutron stars, related to their extreme magnetic fields. Recent detections of pulsed radiation from other stars such as the ultracool dwarf TVLM 513-46546 (hereafter TVLM 513; Hallinan et al. 2006, 2007) and the magnetic chemically peculiar star CU Virginis (HD124224; Trigilio et al. 2000, 2008), however, have provided new insights into the behavior of stellar magnetic fields. Liang & Liang (2007) put forth a magnetic oscillation model (hereafter the MO model) which relates pulsed radiation to the solar cycle model. Thus, observational support for the MO model would significantly enhance the solar cycle model too.

A fundamental assertion of the MO model is that radio pulses (at least narrow pulses) always appear close to the zero point of magnetic field intensity. The observations of Trigilio et al. (2000) indicate that this is the case for CU Virginis. While this is just one star, we think it unlikely that the result is pure coincidence. We therefore propose further investigation of the phase relationship between magnetic field intensity and radiation, in order to determine whether this correlation is a universal phenomenon.

Another claim of the MO model is that like the sun, all stars reverse their magnetic field periodically. Only the frequency of this reversal is different. Near points (b) and (e) in Fig. 2 where the magnetic field reverses direction, the rate of change in magnetic flux is greatest and a very strong electromotive force is induced. This causes charged particles to circulate at very high speed, producing a pulse of gyroscopic or synchrotron radiation. The observed radiation is pulsed because the magnetic field only changes quickly over short periods around point (b) and point (e). Furthermore, since the magnetic field intensity is zero at points (b) and (e), the radiation drops to zero halfway through the pulse. The radiation profile is therefore composed of four pulses per period: \( P_1 \), \( P_2 \), \( P_3 \) and \( P_4 \) depicted in Fig. 2.
The situation described above has been simplified, of course. For one thing, the magnetic field intensity may not follow a sinusoidal pattern. Thus, while the magnetic field always goes through zero twice, its derivative might be different for each pulse. The peak speeds attained by charged particles in the magnetic field will vary accordingly, as will the amplitudes of pulses \( P_1, P_2, P_3 \) and \( P_4 \). It is possible for weaker pulses to be overwhelmed by noise and escape detection. It is therefore normal to receive only one, two, or three pulses per period rather than all four.

The MO model assumes that the magnetic axis of a star always aligns with its spin axis. Liang & Liang (2007) pointed out that if the line of sight aligns with this axis, the radiation should exhibit circular polarization. In this case the order of pulse polarizations, assuming all pulses are detected, should be LCP → RCP → RCP → LCP → LCP as shown in the middle panel of Fig. 2.

The radio light curves shown in Fig. 3 are reproduced from Hallinan et al. (2007) who detected radio emission from TVLM 513. According to the MO model, 100% circular polarization indicates that both spin axis and magnetic axis are aligned with the line of sight. In Fig. 3 pulses \( P_5 \) and \( P_6 \) on the corresponding polarization curve are both left-handed. This result does not accord with the MO model shown in Fig. 2. It may be that something went wrong in processing these data. In another observation of the same star (Hallinan et al. 2006), we found that pulse \( P_6 \) was clearly right-handed.

In order to better distinguish reversal and rotation, we propose more intensive observations of the Phase relationship between magnetic field intensity and pulsed radiation in TVLM 513. The main goals of this program would be to determine whether the magnetic field intensity really goes through zero at point A between \( P_1 \) and \( P_2 \), and to improve the surrounding polarization measurements (Fig. 3). Especially, if the line-of-sight and transverse magnetic field intensities are both observed to go through zero at point A, we
can conclude that magnetic field reversal is indeed taking place and producing the pulsed radio signal.

Another prediction of the MO model is that in the most of cases, the largest pulses appears to the right of a zero point in the magnetic field (e.g., P2 in Fig. 3), because the induced electromotive force reaches its maximum by and large at the zero point of magnetic field, the charged particles should reach their maximum speed sometime after the zero point generally. This prediction can be verified in cases where the pulses are narrow.

2.5. Relationship between Radio Pulse Duty Cycle and the Magnetic Field Profile

Some dwarf stars, for example 2MASS J00361617 + 1821104 (Hallinan et al. 2008), produce radio pulses with a high duty cycle. In other stars, such as TVLM 513, the duty cycle is very low. The duty cycle can also provide some information on changes in the magnetic field.

According to the MO model, radio radiation is intrinsically pulsed. The pulse’s duty cycle depends on the profile of magnetic field. If the field profile is close to a square wave, the duty cycle will be low. If it is close to sinusoidal, the duty cycle will be high.

A rotating magnetic field will always have a sinusoidal profile and there will be no the above relationship between duty cycle and the magnetic field profile. Consequently, whether a star’s magnetic field rotates or reverses can be determined by measuring its duty cycle and magnetic field profile synchronously.
2.6. Relationship between Radio Pulse Polarization and the Magnetic Field

As previously mentioned, the MO model assumes that the magnetic axis and spin axis are always aligned. This implies certain relationships between radio polarization and the spin inclination:

1. If the spin inclination is zero, circular polarization will be detected.
2. If the spin inclination is 90 degrees, linear polarization will be detected.
3. At other inclinations, elliptical polarization will be detected.

From the above relationships, the following can be derived:

1. If the observed radio pulse is 100% circularly polarized, no transverse magnetic field will be observed.
2. If the observed radio pulse is 100% linearly polarized, no line-of-sight magnetic field will be observed.

As the above statements are only true under the MO model is correct, verifying (or refuting) them can reliably determine whether the magnetic field reverses (or rotates).

Because the measurement for both the transverse magnetic field and the line-of-sight one depends on the measurement of polarized spectral line, this method in nature is a measurement of the relationship between radio polarization and line spectrum polarization.

Note that Faraday rotation due to light passing through the magnetosphere and various depolarization effects have been neglected in this method. These factors may create a more complicated relationship between radio pulse polarization and magnetic field. In any case, the investigation on the relationship between radio signal and line spectrum should provide new insights into the behavior of stellar magnetic fields.
3. Discussion

Babcock (1958) found that all typical $\alpha$-variables exhibit a fair degree of symmetry about the $H = 0$ axis in their reversals. That is to say, the polarity of all of the magnetic fields reverses symmetrically. It is very difficult to explain this result using the oblique rotator model. Up to now, Babcock’s result constitutes the most convincing evidence for the solar cycle model. The observation that radio pulses from CU Virginis appear close to the magnetic field null also favors the MO model, which is based on the solar cycle model. Although both results support the magnetic field reversal interpretation, the magnetic field reversal model is not acceptable to many people. The main reason is that the turbulent dynamo model cannot achieve periods under the order of a few days — to say nothing of the millisecond cycles typical of pulsars.

We put forth that the turbulent dynamo model is still unsupported, and thus should not be taken as evidence for against magnetic field reversals. Rather, more observing methods should be developed to determine whether stellar magnetic fields reverse or rotate. If all the observations described in this paper support a magnetic field reversal, the present turbulent dynamo model will have to be modified (or even ruled out).

Noteworthily, some results of data processing, such as Morin et al. (2008) and Silvester et al. (2008), seem to be evidence to support magnetic field rotation. In fact, these results need on the contrary to be supported by the magnetic field rotation model. If magnetic field reverses, and rotation model is wrong, all of the data processing to convert time-domain signals into the three-dimensional image data are only pure mathematical manipulations, without any really physical significance. It is entirely possible that the reversal and oscillation of magnetic field can influence the apparent elemental abundance of star and the characteristics of spectral line and then the periodical time-domain signals emerge.
If the magnetic field reverses, then most periodic stellar phenomena ($v \sin i$, H\textsc{$\alpha$}, apparent elemental abundance, luminosity, pulse radiation, etc.) should vary on the magnetic cycle and bear no direct relation to the rotation period. (Note, however, that the star’s rotation rate exerts a direct influence on its internal dynamics, and may therefore affect the period of magnetic field reversal). If observations of dwarf stars can authenticate reversal periods on the order of hours, the prevailing model of magnetic field generation will have to be changed. Its replacement (for example, the unipolar dynamo model) may be able to explain the very short reversal periods, from hundreds of seconds to milliseconds, observed in white dwarfs and pulsars.

If believing that the sun is a common dwarf star, it should be believed that most of dwarf stars in the sky have alternating magnetic field which is similar to the sun’s magnetic field. If a quasi-stationary magnetic field with a very big magnetic dip angle really exists in some stars, it means that there are two kinds of magnetic fields, the alternating magnetic field and the quasi-stationary one. The questions will be followed. Which are alternating ones or quasi-stationary ones? What conditions can decide the type of magnetic field in a star? What is the low limit of periods for the sun-like magnetic field? In order to explain these questions, some reliable methods should be found to distinguish one type of the magnetic field from another. This paper showed just an attempt to find such methods.
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Fig. 1.— Relationship between line-of-sight and transverse magnetic field components in the two models. The upper panel shows a rotating case, where the phase difference is 90 degrees. The lower panel shows a reversal process, where the two components have the same phase.
Fig. 2.— Relationship between magnetic field intensity and radio pulses. Because the magnetic field intensity is zero at point (b), radiation produced during the (a)-(c) period will be split into the two sub-pulses $P_1$ and $P_2$. In the same way, the pulse produced during the (d)-(f) period will be split into sub-pulses $P_3$ and $P_4$. Left- and right-handed circular polarizations are marked by LCP and RCP. When the line of sight aligns with the rotation axis, the polarization of $P_1$ will be opposite to that of $P_2$. Similarly, the polarization of $P_3$ will be opposite to that of $P_4$. Because their magnetic field directions are the same, however, the polarization of $P_2$ is identical to that of $P_3$. 
Fig. 3.— Radio light curves detected from TVLM 513, reproduced from Hallinan et al. (2007), where the right circular polarization is represented by positive values. The dashed line represents the phase of the magnetic field, as predicted by the MO model. The magnetic field null is at point A, between $P_1$ and $P_2$. 