Surface Imaging of LO Pegasi via Light-curve Inversion

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Purpose

The purpose of this research was to map the starspots on LO Pegasi (HIP 106235), a K8 main-sequence star which is a rapidly rotating \( (P = 10.17 \text{ hr}) \) young solar analog. The brightness of LO Pegasi exhibits quasiperiodic variations because starspots enter and leave the field of view of Earth as the star rotates. Starspots are believed to be analogous to sunspots, so that they are associated with regions of the star that have a much greater magnetic field strength than the surrounding photosphere. Thus, starspots allow the magnetic activity on the stellar surface to be mapped. By studying starspot formation and movement on the surface of the star, greater insight into the stellar surface can be gained.

Procedure

Digital images of LO Pegasi were obtained during May, June, and July 2009 through B, V, R, and I photometric filters using a 0.2-m Meade Instruments LX200 Schmidt-Cassegrain telescope and Santa Barbara Instruments Group ST-8XE CCD camera. Dark frame subtraction and flat field correction were done, and then differential aperture photometry was performed on the images using Mira Pro software from Miriametrics. Using multiple filters improves the latitude resolution by taking advantage of variations in limb darkening between the filters.

The magnitudes were then converted to intensities and the observation times converted to rotational. The rotational phase is the fraction of a rotation through which the star has turned compared to its configuration at an arbitrary starting time.

The Light-curve Inversion (LI) algorithm we used reconstructs the target star's surface by modeling it as a sphere separated into \( N \) latitude bands. The first band surrounds the visible pole, which is defined to be the north pole. Zero longitude is taken to be the latitude band is subdivided into \( M \) patches, with \( M_i \) being proportional to the cosine of the latitude (to within the constraint that it must be an integer) so that all the patches have nearly equal areas. Neglecting interstellar and atmospheric absorption, the intensity at Earth at the time \( t_n \) of the \( k \)th observation through the \( n \)th filter is approximately

\[
I_{nk} = \sum_{i=1}^{M_i} \sum_{j=1}^{J_{ij}} \Omega_{nkij} L_{nkij} J_{nkij},
\]

where \( \Omega_{nkij} \) is the solid angle subtended by patch \((i,j)\) at time \( t_n \), \( L_{nkij} \) is its limb darkening (the ratio of the specific intensity along the line of sight to the specific intensity along the outward normal), and \( J_{nkij} \) is the specific intensity along the outward normal as seen through filter \( n \). This approximation becomes exact in the limit of an infinite number of patches.

The goal of LI is to produce a set of patch intensities \( I_{nkij} \) which reproduces as closely as possible the actual brightness variations on the stellar surface. We cannot simply find the set which produces the best fit to the light curve data. If numerous small spots peppered the surface, at any given time nearly equal numbers would be appearing at the approaching limb and disappearing at the receding limb, so that the effect would be to impart a small, noise-like ripple on the light curve. Conversely, that if we simply optimize the goodness-of-fit to the data, the reconstructed surface will be peppered with spurious small spots which attempt to account for the noise in the data.

To avoid this, we perform a constrained non-linear inversion by finding the set of \( I_{nkij} \) which minimizes the objective function

\[
E(J, I, \lambda, B) = G(J, I) + \lambda S(J, B),
\]

where \( G \) is a function that measures goodness-of-fit between the data light curve and the light curve of the reconstructed surface, with smaller \( G \) implying a better fit; \( S \) is a smoothing function which expresses the "smoothness" of the reconstructed surface, with smaller \( S \) implying a smoother surface; \( \lambda \) is the tradeoff parameter; and \( B \) is the bias parameter (see below). As \( \lambda \to 0 \), \( G \) dominates, so that minimizing \( E \) produces the best-fit solution with resulting noise artifacts, while as \( \lambda \to \infty \), \( S \) dominates and we obtain a featureless surface which does not match the variations in the data at all. Thus, for some intermediate value of \( \lambda \), we obtain a solution which fits the data well, but not to any greater a degree than is justified by the noisiness of the data, thus avoiding the problem of having noise artifacts dominate the reconstruction.

For the goodness-of-fit we used

\[
G(J) = \frac{(2.5 \log_{10} e)^2}{P} \sum_{n=1}^{Q} \frac{1}{G_n^2} \sum_{k=1}^{P} \left( \frac{I_{nk} - I_{nk}^*}{I_{nk}^*} \right)^2,
\]

where \( I_{nk}^* \) is the measured intensity at time \( t_n \), \( G_n \) is the estimated variance expressed in magnitudes between the measured and calculated light curve intensities for filter \( n \), \( P \) is the number of points for filter \( n \), \( P \) is the combined number of points in all the light curves, and \( Q \) is the number of light curves. It can be shown that \( G \to 1 \) when the overall residual between the calculated and data light curves is equal to the estimated noise variance.

For the smoothing function we used

\[
S(J, B) = \sum_{i=1}^{N} \sum_{j=1}^{M} c_{ij} (J_{i,j} - J_{i,\text{avg}})^2;
\]

The bias parameter \( B \), which is greater than 1, favors surfaces that have a small number of dark patches (that represent the spots) and many patches just slightly brighter than average (that represent the photosphere). This is because as patches deviate from the average in order to fit the light curve data, the "penalty" (increase in \( E \)) for a patch being brighter than average by a given amount is \( B \) times greater than if it were darker by the same amount. The motivation for this is the fact that on the Sun, sunspots are embedded in a photosphere of nearly uniform brightness.

Results

The images above were produced using data from the summers of 2006–2009, showing how the surface of LO Pegasi has evolved over time. Composite B light curves from 2008 and 2009 are shown at the bottom. It is interesting to note that when the light curves from both years are compared, LO Pegasi in 2009 is seen to be dimmer overall than it was in 2008. This is most likely caused by the presence of a spot on the visible pole. Because polar spots do not modulate the light curve (always being in the field of view), they only decrease the overall total brightness of the star. The LI photometric inversion program does not image polar spots. However, Doppler imaging (Lister et al. 1999, MNRAS, 307, 685) indicated the presence of both mid-latitude spots and a polar spot with projections to lower latitudes.

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