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STARSPOTS ON THE YOUNG SOLAR-TYPE STAR π^1 URSAE MAIORIS

BOCHANSKI, J.J.; GUINAN, E.F.; DEPASQUALE, J.M.; MC COOK, G.P.

Astronomy & Astrophysics Department, Villanova University, Villanova, PA 19085, USA

π^1 Ursae Maioris (HD 72905, G1.5 V, $V = +5.63$, $B-V = +0.62$, $\pi_{\rm Hip} = 70.07 \pm 0.71$ mas) is a single solar-type star that has high levels of chromospheric and coronal X-ray emissions (Dorren & Guinan 1994; Gaidos 1998). The U, V, W space motions indicate that π^1 UMa is a member of the Ursa Maioris Star Stream with an age of $\sim$ 350 Myr (Soderblom & Mayor 1993). Selected as a proxy for the young Sun some 4.2 Gyr ago and included in Villanova's *The Sun in Time* program, π^1 UMa has physical properties (except for age) similar to the Sun ($T_{\rm eff} \approx 5860$ K, [Fe/H] ≈ -0.08, $M \approx 1\ M_\odot$ and $L/L_\odot \approx 0.96$) (Gaidos 1998). *The Sun in Time* program (Dorren & Guinan 1994) is a multiwavelength study of solar-type stars (G0-5 V) ranging in age from Zero Age Main Sequence (ZAMS) to Terminal Age Main Sequence (TAMS).

The age associated with the membership of π^1 UMa in the UMa Star Stream is consistent with the observed high levels of coronal and chromospheric activity. This star is a moderately strong coronal X-ray source, with an X-ray luminosity $L_{\rm x} \approx 1.3 \times 10^{29}$ erg s^{-1}, approximately 40 times more luminous than the Sun (Guinan et al. 2000). X-ray flaring has also been observed on π^1 UMa, in particular a large X-ray flare recorded by the EXOSAT satellite during January 1984 (Landini et al. 1986). It also displays enhanced Mg II h+k and Ca II H+K chromospheric emissions. From Mt. Wilson Ca II K-line spectrophotometry, π^1 UMa is found to have about two times the Ca II emission of the Sun (Baliunas et al. 1995). This heightened activity throughout the upper atmosphere of the star is consistent with its young age and short rotation period ($P_{\rm rot} \approx 4.8$ days) that results from a more vigorous magnetic dynamo, as discussed below.

Differential photoelectric photometry of π^1 UMa was carried out using the 0.8-m Four College Consortium (FCC) Automated Photoelectric Telescopes (APT) located in Southern Arizona. The observations were conducted on more than 350 nights from October 1990 to March 2000, using *UBVRcIc* filters. Using an integration time of 10 seconds, over 1500 observations were secured in each filter. Typically the observations were carried out for about 25 minutes per night. The observing sequence was the usual pattern of *sky–comparison–check–variable–comparison–sky*, employing HD 73108 (K1 III, $V = +4.60$, $B-V = +1.19$) as the primary comparison star. HD 72037 (A2m, $V = +5.46$, $B-V = +0.20$) served as the check star. The data were corrected for atmospheric extinction, using extinction coefficients determined from the analysis of the comparison star and standard stars. Both the comparison and check stars lie within $\sim$ 1.5 degrees of π^1 UMa. Because of this, the resulting corrections for atmospheric extinction were always small. The photometry of the comparison and check stars show that both stars are constant in brightness to levels of less than ~ 6 mmag. This is confirmed by Hipparcos photometry where $\sigma_{\rm Hip} = 0.0006$, $\sigma_{\rm Hip} = 0.0005$ are given for the comparison and check star respectively.

To illustrate the photometric behavior of π^1 UMa, all of the V-band observations are plotted against Julian Day in Figure 1. The small open circles are the individual observations and the large filled circles represent 2 to 3 month brightness averages. As shown in the figure, long-term changes in the brightness are easily seen. When examined on an expanded time scale, the apparent "scatter" in the individual observations arises from low amplitude ($\sim 0\overset{\rm m}{.}020$–$0\overset{\rm m}{.}035$) periodic light variations with a period of $P \sim 5$ d. Similar brightness variations are found for the other data sets at different wavelengths. As in the case of other cool chromospherically-active stars, the low amplitude light variations most likely arise from an uneven distribution of cool starspots in the photosphere of the rotating star. As shown in the figure, the difference in the mean V-mag between the minimum brightness (1990–1992) and maximum brightness (1995–1998) is about $0\overset{\rm m}{.}035$. The present observations suggest a possible cycle length of 12-13 years. As discussed by Messina et al. (1999), the variations in the light amplitudes for similar solar-type stars primarily arise from the effects of differential rotation and varying starspot areal coverage. When the longitudinal separation of the two spot regions is less than $\sim 60°$ the spots appear on the same hemisphere of the star and produce the larger rotational modulated light variations. The lower amplitude light variations occur when the spots are separated in longitude by $\sim 180°$ or when the spots drift toward the rotational pole (or both). For example, the 1993 and 1996 light curves have the smallest light amplitudes while 1991, 1992 and 1995 light curves have the relatively large light amplitudes. Also note that in some years (e.g., 1990/91, 1994, and 1995) the mean light levels and light amplitudes appear to change very rapidly — i.e., on a time-scale of several weeks. In a future paper we plan a detailed analysis of all of the photometry that will include an investigation of differential rotation and variations in spot coverage.

It is not within the scope of this paper to discuss the entire data set. For illustrative purposes, the 5-colour photometry of π^1 UMa obtained during a run of clear nights in April 1991 is discussed and analyzed. We examined other data sets and this data set is representative of the light variations of π^1 UMa, and displays good coverage of the star's light curve. Small, sinusoidal-like light variations are apparent and it is clear that π^1 UMa is a low amplitude variable star. There is a definite wavelength dependence in the light amplitude. The light amplitudes found during April 1991 are: $U:\ 0.054 \pm 0.006$, $B:\ 0.038 \pm 0.005$, $V:\ 0.032 \pm 0.005$, $Rc:\ 0.030 \pm 0.004$, and $Ic:\ 0.027 \pm 0.005$.

The April 1991 photometry was analyzed with the Scargle–Press period search routine (Scargle 1982) and a period of $P_{\rm ptm} = 4.79 \pm 0.08$ days was found. Period searches of other subsets of data indicate that the period is variable with time. Preliminary period studies of the 1990-2000 observations indicate that the period ranges from $P \sim 4.6$ to 5.1 days. This range of apparent periods is similar to the periods of $P \approx 4\overset{\rm d}{.}6$–$4\overset{\rm d}{.}82$ found by Donahue (1993) from the Scargle (1982) periodogram analysis of Ca II H+K spectrophotometry obtained at Mt. Wilson from 1984–1991. More recently, Gaidos et al. (2000) report periods between $4\overset{\rm d}{.}62$–$5\overset{\rm d}{.}46$ and a mean period of $4\overset{\rm d}{.}89$ from the photoelectric photometry made during 1993–1999. For chromospherically-active stars like π^1 UMa, the observed photometric period is the rotation period of the surface of the star, where the spots are located. The observed variations of the photometric period most likely arise from differential rotation as starspots form at different stellar latitudes, perhaps over an activity cycle. From its periodic low amplitude light variations and its high levels of chromospheric and coronal activity, π^1 UMa should be classified as a BY Draconis variable star.

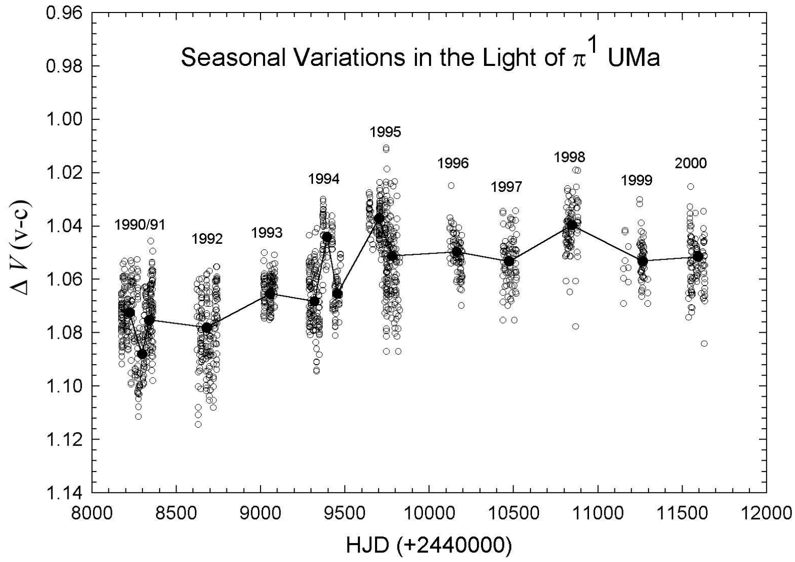

Figure 1. The V-band light variations of π^1 UMa in the years from 1990 through 2000 are plotted versus time. Long-term (possibly cyclic) changes in the mean brightness are shown. The numerous small open circles are the individual 10-second observations; the larger filled circles are approximately 2 to 3 month brightness means. As discussed in the text, the apparent scatter within the seasonal data sets arises primarily from the rotational modulation of brightness from starspots

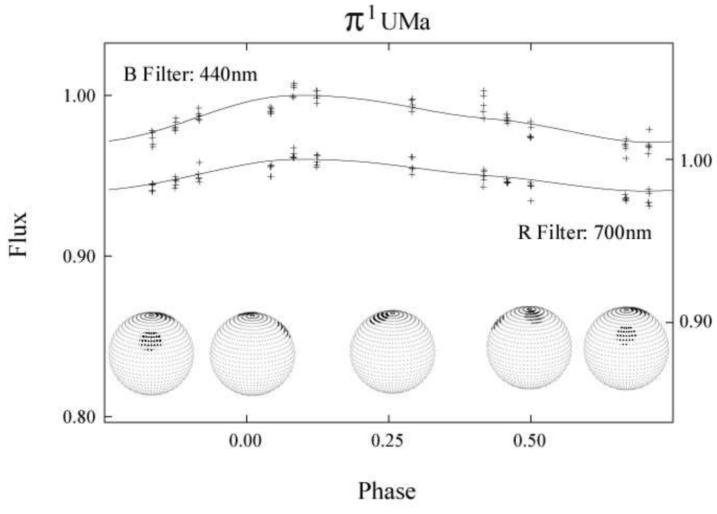

Figure 2. The normalized intensities from B and Rc photometry of π^1 UMa are plotted versus photometric phase. The observations were carried out during April 1991. The phases were computed with the $P_{\rm ptm} \approx P_{\rm rot} = 4\overset{\rm d}{.}79$. The best fitting spot model curves (see text) are shown among the observations and the corresponding 3-dimensional representations of the spot configuration on the star's surface are depicted at four different phases: 0.75, 0.00, 0.25, and 0.50

The light curves were analyzed on the assumption the light variations arise from starspots using a modified version of Binary Maker 2.0 (Bradstreet 1993). Spots of uniform temperature and circular shape were assumed, and a photospheric $T_{\rm eff}$ of 5860 K (Cox 2000), appropriate for its G 1.5 V spectral type was adopted. An inclination of about 70° (angle of the stellar pole relative to the line of sight) was used, as calculated from a $v \sin i = 9.5$ km s^{-1} (Soderblom 1982; Fekel 1997), and a stellar radius of $R \approx 1\ R_{\odot}$ as inferred by the spectral type. The photometric data used in analysis was phased using an arbitrary time of minimum light and $P_{\rm ptm} \approx P_{\rm rot} = 4.79$ days. These observations were normalized and transformed to intensity units. For the modelling we use the effective wavelengths and the transmission functions of the different filters. The B and R observations are shown in Figure 2 along with the best-fitting model fits. Below the light curves in Fig. 2 is the geometric representation of the star with starspots, shown at different rotation phases. The $UBVRcIc$ light curves were fit using manual iteration. For April 1991, π^1 UMa was found to have two mid-latitude spots located at latitude $\approx 40° \pm 25°$ and the other at $65° \pm 15°$. The spots have a longitudinal separation of $\Delta \ell \approx 110° \pm 15°$. Both spots were about $14° \pm 3°$ in radius, resulting in a total spot coverage of the star of about 3%, or if symmetry about the stellar equator is assumed (as seen in the Sun), the spot coverage can be as high as $\sim 6\%$, depending on spot latitude. This spot coverage is about 30 times greater than observed for the Sun ($\sim 0.2\%$), even during the maximum of the sunspot cycle (Cox 2000). The temperature difference between the cooler spots and the photosphere was found to be $\Delta T \approx 500 \pm 100$ K. This quantity is well constrained from the wavelength dependence of the light variations. However, because of the low amplitudes of the light variations and the lack of contemporaneous Doppler imaging, there are large uncertainties in the latitudes of the spots. Thus the values found for the starspot properties are not unique. However, they should be considered as representative of spot areas, distributions, and temperatures at the time of observations.

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