POLARIMETRY OF STELLAR ACTIVE REGIONS AND FLARES

I. TUOMINEN, J. HUOVELIN

Observatory and Astrophysics Laboratory, University of Helsinki, Tähtitorninmäki, SF-00130 Helsinki, Finland

and

YU. S. EFIMOV, N. M. SHAKHOVSKOY, and A. G. SHCHERBAKOV

Crimean Astrophysical Observatory, P/O Nauchny, SU-334413 Crimea, U.S.S.R.

Abstract. Observations of regular and irregular polarimetric variability in late-type stars are reviewed, and the related physical and geometrical effects are discussed. There are indications that the irregular part of the variability could be caused by transient events, possibly associated with flares. Polarimetric observations during flares are reviewed, and preliminary results of new observations of a well-known flare star, YY Geminorum, are presented. The results show that the small flare in YY Gem did not cause any significant variations in linear polarization, while the binary eclipse evidently causes an enhancement in the polarization. The reasons for the difficulties in stellar flare polarimetry are discussed. Finally, future prospects for the observations of flaring stars and for the utilization of linear polarimetry as a complementary method to other techniques of surface imaging of stellar activity and flares are presented.

1. Introduction

Magnetically active late-type dwarfs and giants have inhomogeneities on their surfaces that cause various observable effects in the spectral lines and light curves. These variations are partly caused by rotational modulation due to more or less permanent inhomogeneities on the stellar surface (i.e., magnetic spots, plages, gaseous or dust disks, gas streams, or 'starpatches'), or changes in the visibility or illumination of the atmosphere of a multiple star.

It is expected that the polarization of the integrated stellar light may change along with the above phenomena. RS CVn stars such as RS CVn (Pfeiffer, 1979), HR 5110 (Barbour and Kemp, 1981), HD 8357 and ER Vul (Liu and Tan, 1987) have shown variations in linear polarization, while most of these close binary stars seem to exhibit constant polarization (see, e.g., Weiler *et al.*, 1978; Liu and Tan, 1987). Most of the BY Dra-type spotted stars and dMe stars (i.e., 'flare stars') have not shown significant intrinsic polarimetric variability (see Efimov and Shakhovskoy, 1972; Pettersen and Hsu, 1981; Clayton and Martin, 1981), while BY Dra itself has been reported to exhibit marginally variable linear polarization (Koch and Pfeiffer, 1976; De Jager *et al.*, 1986).

Ordinary single late-type dwarfs seldom have significant irregular variations in their spectra and they usually show almost constant brightness in the optical region. RS CVn stars, BY Dra stars, FK Com stars, and dMe stars, on the contrary, often show various types of irregularities mixed with rotational modulation. The more irregular changes that sometimes dubiously resemble instrumental effects or variations due to telluric atmosphere are, in many cases, probably caused by transient phenomena qualitatively similar to those on the Sun. During these events, magnetic energy is suddenly released

Solar Physics **121:** 419–429, 1989.

in the form of electromagnetic and particle radiation. The most intense of these phenomena on the Sun are flares that may cause brightening in the whole continuum from X-rays to radio waves, and intensified emission in many spectral lines, such as the chromospheric ultraviolet lines and the Hα line.

Since flares are closely related with magnetic activity and inhomogeneities on the stellar surface, one would expect to also see variations in the polarization during stellar flares, although the essential mechanism is not yet clear. In this report, we shall discuss suggested polarization mechanisms in late-type stars, review polarimetric observations of flaring stars, introduce new observations of YY Gem (Castor C), and finally discuss the interpretation and future prospects of stellar flare polarimetry.

2. Polarization in FK Comae, HD 199178 and Late-Type Dwarfs

The peculiar active GS giant FK Com and another chromospherically active G5 (sub)giant HD 199178 have shown significant variations in the broadband linear polarization (Piirola and Vilhu, 1982; Huovelin *et al.*, 1987). The variations in HD 199178 are apparently close to phase locked polarization (see Figure 1(a)), matching the photometric period of 3.337 days determined by Bopp *et al.* (1983). The polarimetric variations in HD 199178 are, however, not stable, as shown by recent analysis by Jetsu *et al.* (1989). The changes are obviously connected with changing photometric variability. Jetsu *et al.* found significant changes in time-scales of few months in the light curves, as well as in the polarimetry.

FK Comae showed more irregular variability (see Figures 1(b–d)), without clear evidence of rotational modulation. Huovelin *et al.* (1987) suggest that the large polarization peak in FK Comae in the *B* band at phase 0.825 (see Figure 1(c)) could be due to a transient phenomenon, such as a flare. Simultaneous observations of other flare indicators were, however, not made.

G- and K-type dwarfs have linear polarimetric variations as well (e.g., Piirola, 1977; Tinbergen and Zwaan, 1981; Huovelin *et al.*, 1985). A few of them also show evidence of low amplitude rotational modulation, as demonstrated by observations of Huovelin *et al.* (1986, 1989) and Huovelin, Saar, and Tuominen (1988). The most regular variations were found in such stars as the G0 dwarf HD 206860 (HN Pegasi), and the G2 dwarf HD 1835 (9 Ceti), both of which also show low amplitude photometric variability (Blanco, Catalano, and Marilli, 1979; Chugainov, 1980), and rotational modulation of the chromospheric Ca II H and K emission (Noyes *et al.*, 1984). The photometric period of Chugainov for HD 1835 (7.655 days) matches well with the Ca II modulation period (7.7 days), while the photometry of Blanco, Catalano, and Marilli for HD 206860 implies a period of 24.9 days in the *V* band, contradicting the period of 4.7 days determined by Noyes *et al.* (1984). A reasonable physical explanation for the discrepancy in the HD 206860 period determinations is difficult to find, if both determinations are correct. The observed polarimetric variations of HD 206860 are demonstrated in Figures 2 and 3 (from Huovelin *et al.*, 1989). The variations match well with the period 4.7 days (Figure 3).

https://doi.org/10.1017/S0252921100032036 Published online by Cambridge University Press

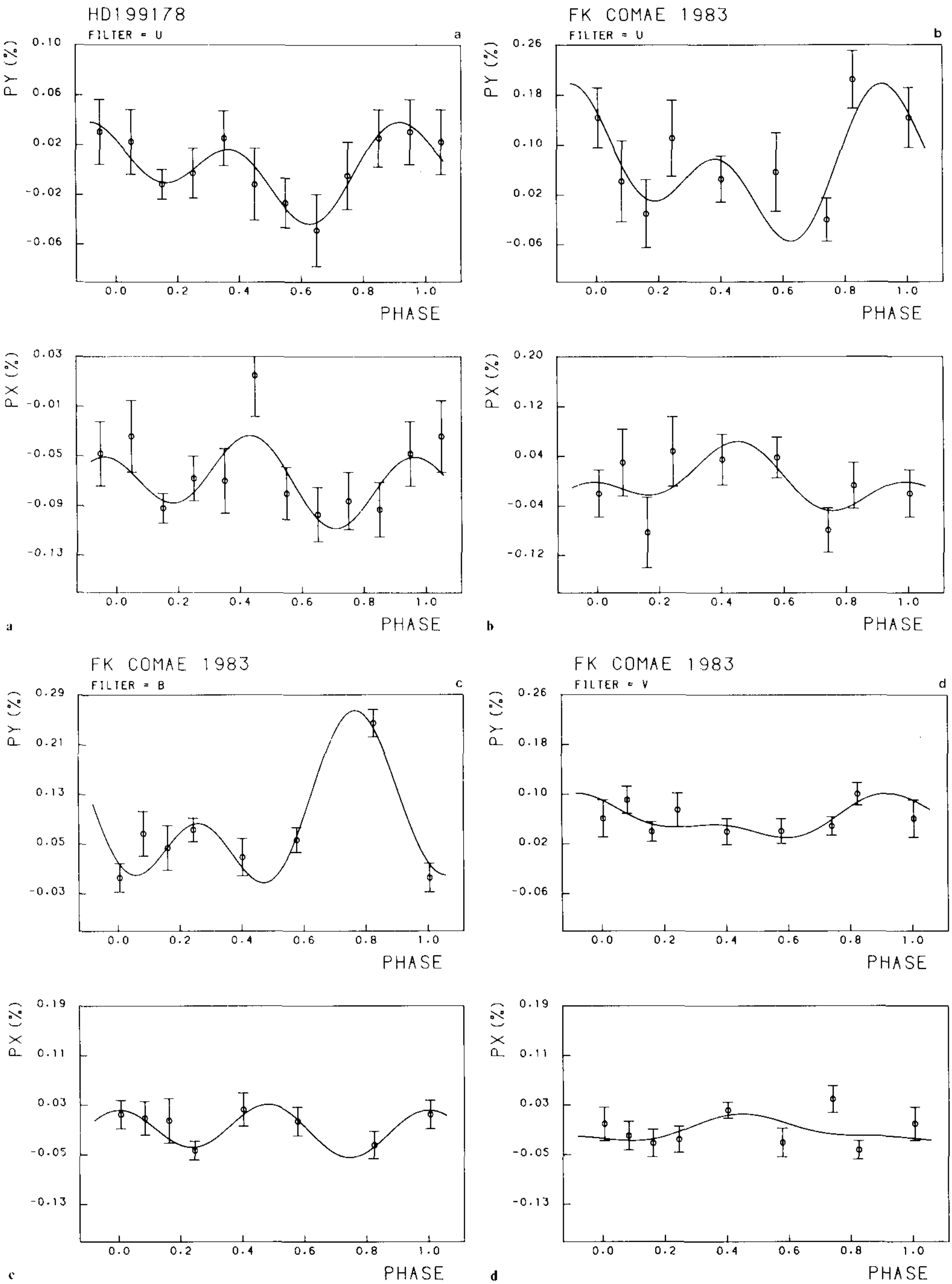

Fig. 1. Normalized Stokes parameters $P_X = P \cos 2\theta$ and $P_Y = P \sin 2\theta$ vs photometric phase for HD 199178 in the *U* band, and for FK Comae in *U*, *B*, and *V*, from Huovelin *et al.* (1987). The continuous lines are second-order Fourier fits, and the error bars give the standard mean errors.

https://doi.org/10.1017/S0252921100032036 Published online by Cambridge University Press

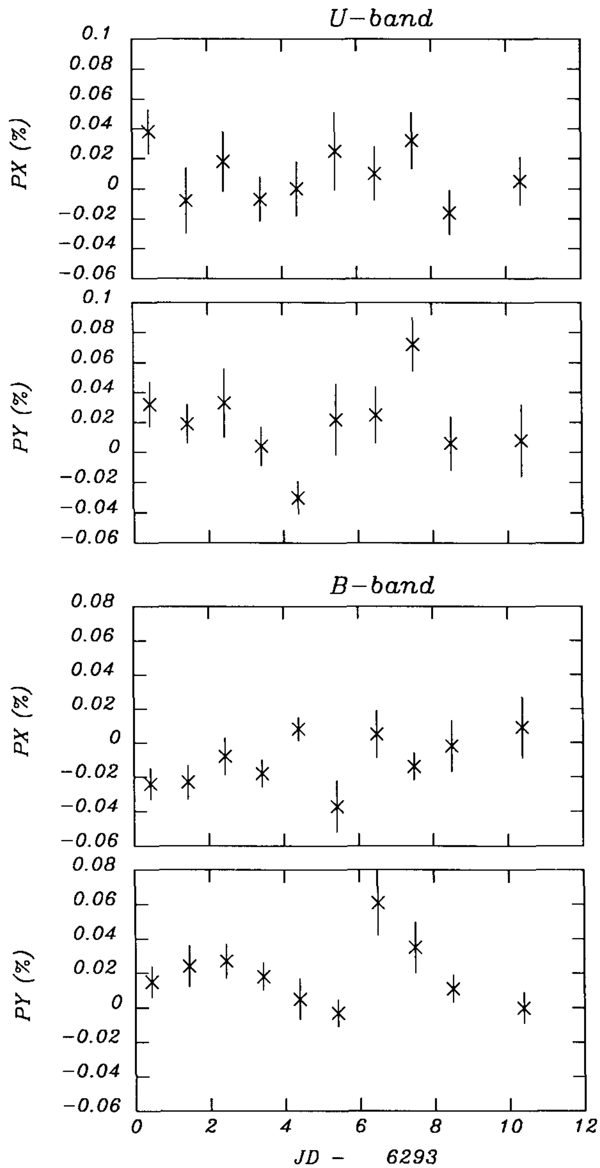

Fig. 2. Nightly averages of P_X and P_Y vs Julian date (2440000 +) for HD 206860 in the U and B, from Huovelin *et al.* (1989). Errors as in Figure 1.

3. Sources and Mechanisms of Polarization

Linear polarization can generally be expected in stars with inhomogeneities or non-isotropic gas flows. These are (1) magnetic areas, i.e., star spots and plages (chromospherically active stars), (2) inhomogeneous circumstellar gas or dust envelopes or disks

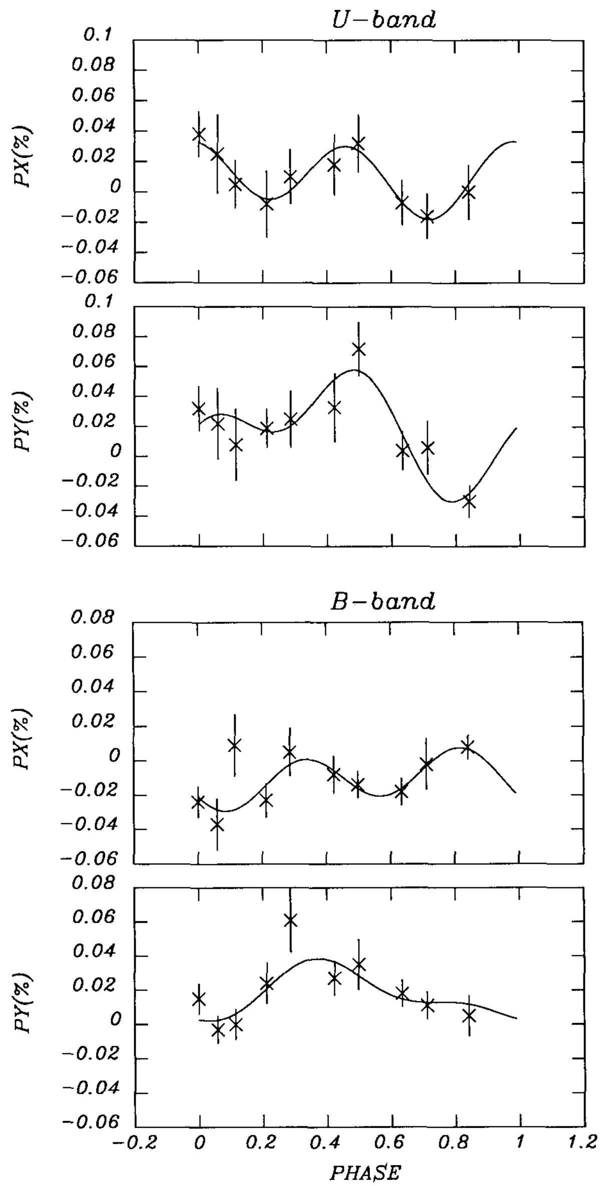

Fig. 3. Observations of Figure 2 as a function of rotational phase, calculated from period 4.7 days. Zero-phase arbitrary. The continuous line is the second-order Fourier fit.

(binaries, giants), (3) gas streams or non-isotropic stellar winds (interacting binaries), and (4) tidal and rotational deformations (rapidly rotating close binaries).

The most popular mechanisms that have been suggested as the source of linear polarization in the above cases are Rayleigh, Thomson, or Mie scattering in an *optically thin* medium (e.g., Shakhovskoy, 1965; Grinin and Domke, 1971; Cassinelli and

Haisch, 1974; Poeckert and Marlborough, 1976; Brown, Mclean, and Emslie, 1978; Pfeiffer, 1979; Piirola and Vilhu, 1982) and magnetic intensification, i.e., the net linear polarization in saturated Zeeman sensitive spectral lines (Warwick, 1951; Leroy, 1962; Kemp and Wolstencroft, 1974; Mullan and Bell, 1976; Tinbergen and Zwaan, 1981; Huovelin *et al.*, 1985, 1986, 1989; Huovelin, Saar, and Tuominen, 1988). Also synchrotron radiation has been proposed as a possible source of polarization, but it would require magnetic fields or electron energies several orders of magnitude larger than observed in the Sun to be effective in the optical region, even during a post-flare outburst of electrons (the frequency of the maximum power in synchrotron radiation increases linearly with the magnetic field and with the square of the electron energy; Ginzburg and Syrovatskii, 1964). Hence, Mullan (1975) concludes that polarization in late-type Main-Sequence stars is most likely *not* due to synchrotron radiation.

The expected wavelength dependence of linear polarization for Rayleigh scattering in optically thin gas is λ^{-4}, while Thomson scattering introduces wavelength independent linear polarization. As for magnetic intensification, the density of saturated Zeeman lines in the given passbands determines the wavelength dependence. It is, therefore, a function of temperature and luminosity of the star. Saar and Huovelin (1989) have calculated models for broadband linear polarization in late-type stars, and their results indicate considerable changes with spectral type and luminosity from a power-law dependence $P \sim \lambda^{-8}$ ($\log g = 4$ and $T_{\text{eff}} = 4000$ K), to $P \sim \lambda^{-2.0}$ ($\log g = 3$ and $T_{\text{eff}} = 6500$ K) in the degree of linear polarization. A comparison with observations supports these predictions (Huovelin, Saar, and Tuominen, 1988).

4. Polarimetry During Flares

Linear polarization during flares has been monitored simultaneously with the usual flare indicators (Hα, photometry) only a few times. Efimov and Shakhovskoy (1972) observed linear polarization in the blue region during the rising and declining phases of a flare in EV Lac with integration times of 20 s. The brightness of EV Lac increased by 1.27 mag, and the duration of the flare was about 20 min. Efimov and Shakhovskoy did not find significant changes in the polarization during the flare.

The polarimetry of YZ CMi in the visual band during the short (about 4 min) flare, reported by Karpen *et al.* (1977), reveals no linear polarization above the 2σ level, although the magnitude in blue increased by about 0.8 mag. Also Eritsian (1978) observed a number of flares in EV Lac and AD Leo in the blue and the visual region, finding no significant differences in polarization between the active and the quiescent phases.

Pettersen and Hsu (1981) observed AD Leo before and during a flare in the ultraviolet region (≈ 360 nm), finding the average polarization of $P = 0.9 \pm 0.6\%$ during the preflare phase, and $P = 0.5 \pm 0.4\%$ during the high intensity phase of the flare (averages over about 10–15 min). The observed complex flare in the ultraviolet consisted of 3 maxima with about 5 min separation between the first and the last peak. Pettersen and

Hsu concluded their result as a nondetection of linear polarization during the flare of AD Leo.

De Jager *et al.* (1986) reported broadband *UBVRI* linear polarimetry observed during a flare of 20 min duration in BY Dra. The brightness of BY Dra increased by about 0.25 mag in the ultraviolet (360 nm), about 0.04 mag in the blue (440 nm), and was practically constant in *VRI*. In the ultraviolet, the average degree of polarization was $P = 0.40 \pm 0.12\%$ during the flare, compared with the average over the whole night $P = 0.056 \pm 0.040\%$. The polarization in *BVRI* was considerably smaller, following the decrease of the brightness with increasing wavelength. The 3σ detection in the ultraviolet can be taken as evidence for flare-induced polarization, although De Jager *et al.* carefully avoid calling it conclusive.

5. YY Geminorum

The spectroscopic double-lined binary YY Geminorum is the weakest component of the sextuple star α Geminorum (Castor). YY Geminorum consists of two almost equally massive stars (Struve, Herbig, and Horak, 1950; Struve and Zebergs, 1959; Bopp, 1974), both classified as dM1e flare stars, with the Hα and Ca II H and K lines in emission (Moffett and Bopp, 1971; Joy and Abt, 1974). The distortions in the observed light curves suggest bright or dark spots on the surfaces of both components (Kron, 1952). The orbital period of this synchronously rotating system is 0.8142822 days (Van Gent, 1931), with very small eccentricity in the orbit (see Bopp, 1974), and almost equally deep eclipses at phases 0.0 and 0.5, indicating an inclination close to 90°.

The polarimetric observations of Pfeiffer and Koch (1973) showed variability with time, which may indicate the existence of a circumstellar cloud around the system, with scattering as the cause of polarization. The polarization has also shown variations in short time-scales (less than 50 min), which may be due to the spots, or changes in the circumstellar material, perhaps during flares (see Bopp, 1974).

New polarimetric observations of YY Geminorum by the present authors were obtained at the Crimean Astrophysical Observatory on March 5 and 6, 1988 with a five-channel (*UBVRI*) version of the double image chopping photometer-polarimeter described by Piirola (1973, 1975), connected with the 1.25 m optical telescope. The observations were made in five passbands, with effective wavelengths 0.36, 0.44, 0.53, 0.69, and 0.83 μm. The photometry was obtained with the same instrument, simultaneously with the polarimetry.

The Hα spectra were also observed simultaneously with the photopolarimetric observations, using the 2.6 m telescope Coudé spectrograph of the Crimean Observatory (10 spectra in the first night and 9 spectra in the second night).

Among other irregularities, a complex and comparatively small flare with two maxima was observed on March 6, at ≈18:00 UT (phase 0.1 to 0.16). The photometric flare was strongest (about 0.2 mag) in the ultraviolet band, and was simultaneous with a brightness depression possibly caused by a dark spot crossing the stellar disk (see Figure 4(b)). The March 5 observations included the primary minimum (Figure 4(a))

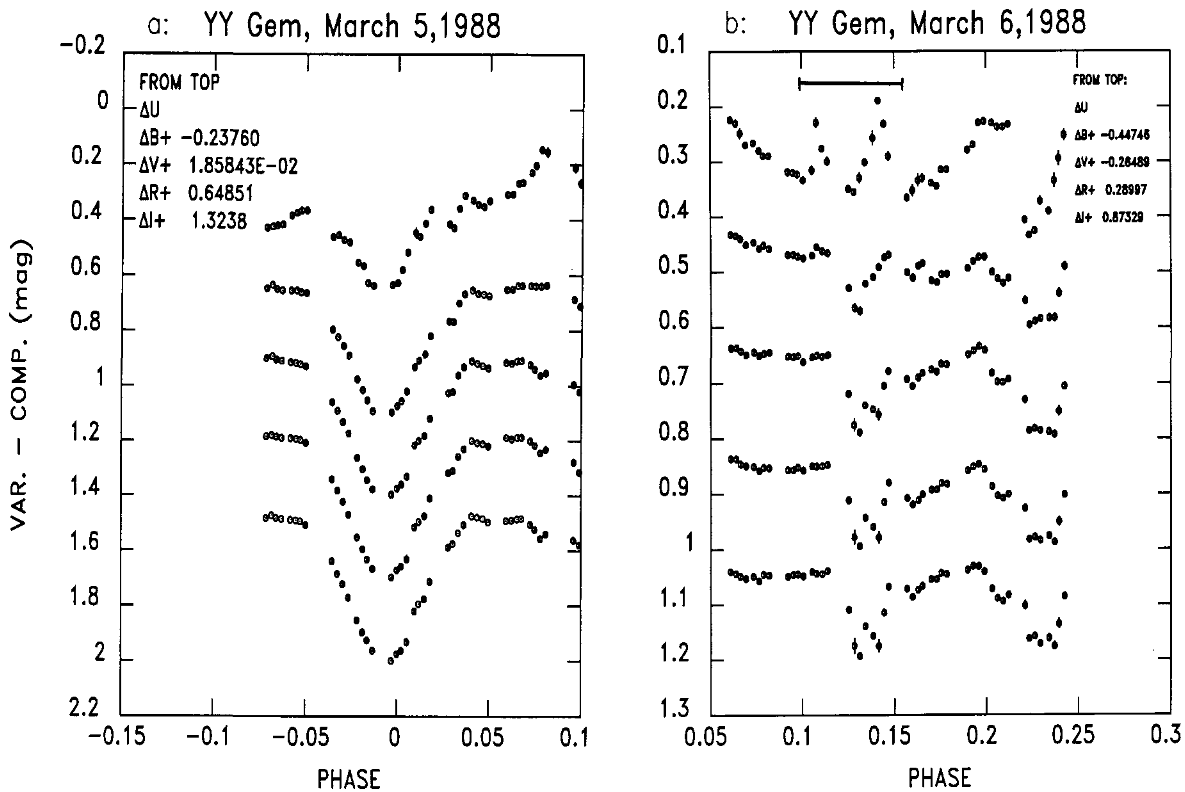

Fig. 4. The photometry of YY Germinorum in standard *UBVRI* system, in (a) March 5 and (b) March 6, 1988. The magnitudes are in the sense (variable − comparison + constant) = (Δ + const.), where the constant is the vertical shift of each light curve. The ephemeris for the phase is T_0 = JD 2424989.1169 and period 0.8142822 days (van Gent, 1931). The flare is seen in (b) between phases 0.1 and 0.16 (indicated by the horizontal bar).

https://doi.org/10.1017/S0252921100032036 Published online by Cambridge University Press

which showed a small phase shift (≈ 5 min/≈ 60 years), indicating very high stability in the system, and high precision in Van Gent's (1931) period determination.

The simultaneous Hα spectrum showed slightly enhanced emission, as demonstrated by a comparison with another spectrum taken one orbital period earlier, when flares were not seen in the light curves. The equivalent width of the Hα emission during the flare was enhanced by about 250 mÅ (i.e., about 10% of the total emission).

The linear polarization is represented in Figure 5. The observations were grouped into independent phase bins with $\frac{1}{40}$ of a period per bin (about 0.5 hr). Each bin contained 5 to 8 observations, which is quite adequate for reliable error estimates. The polarization variations on March 6 (Figure 5(b)) were the most significant in the ultraviolet (U), while the other bands ($BVRI$) showed variations below 1σ. The degree of polarization during the flare was $P = 0.318 \pm 0.193\%$, which is not significantly different from the nightly average. A slight increase was observed during the post-flare phase 0.15 to 0.175 ($P = 0.634 \pm 0.235\%$), and the polarization was again lower during the phase 0.175 to 0.2 ($P = 0.396 \pm 0.193\%$). Thus, considering the error limits, the above results do not represent conclusive evidence for significant variations in the polarization due to the flare.

There was, however, significant difference in the average polarization on March 6 ($P = 0.335 \pm 0.082\%$) compared with the average of observations on March 5 ($P = 0.635 \pm 0.093\%$). The difference is probably connected with effects due to the

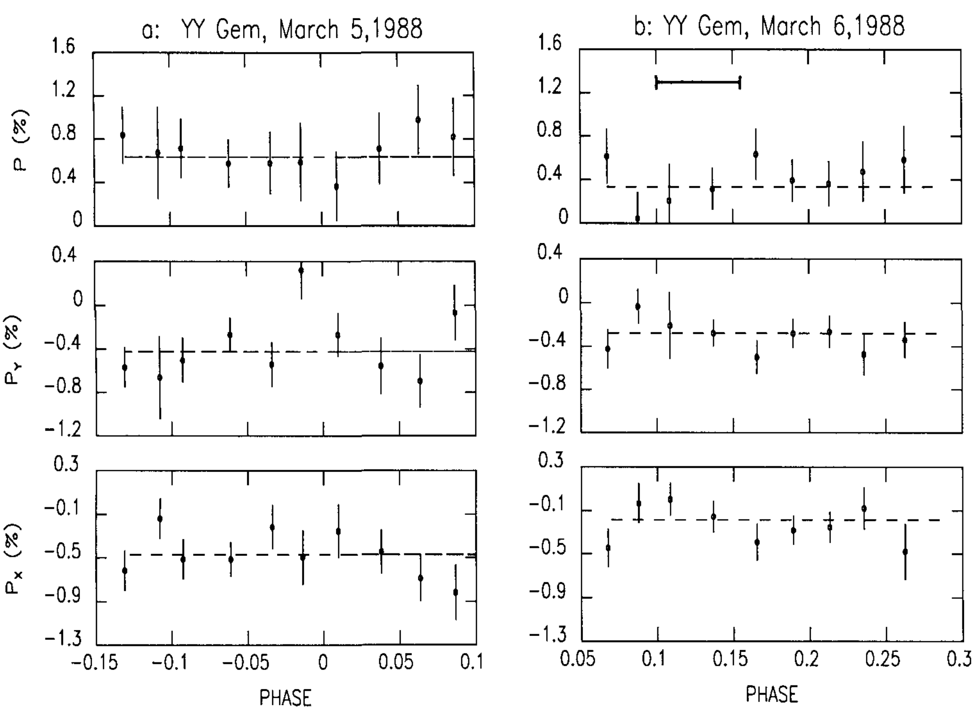

Fig. 5. The Stokes parameters and the degree of polarization in (a) March 5, and (b) March 6. The horizontal bar in (b) shows the time of the flare. The dashed lines show the nightly averages.

https://doi.org/10.1017/S0252921100032036 Published online by Cambridge University Press

eclipse. Perhaps there is a circumstellar envelope or cloud that was asymmetrically illuminated near the time of the eclipse, causing the enhancement of the linear polarization.

6. Conclusions and Discussion

The polarization changes during and after stellar flares seem to be very difficult to detect, as shown by both previous and our new observations. Given the time resolution and observational accuracy, the observed polarization changes are only suggestive. The lack of observational evidence for a polarization enhancement during flares can be explained using the following arguments.

(1) Flares near the stellar disk center are the most intense and are the most easy to observe with photometry and spectroscopy. However, the expected linear polarization due to scattering or magnetic intensification will be small if the flare is observed face-on, since the linear polarization should be zero if the polarizing region is at the line-of-sight from the stellar disk center, while the maximum for simple scattering occurs at 90°, and for magnetic intensification at 45–55° from line-of-sight (Unno, 1955; Saar and Huovelin, 1989). We should, therefore, expect to see higher polarization with flares close to the stellar limb, instead of a hopeless search for a correlation between the flare intensity and the degree of linear polarization.

(2) Flares usually last only from a few to 10 min, causing large photometric variations. Large errors in polarimetric observations inevitably follow from rapidly changing brightness. Very short integration times, on the other hand, are followed by a low level of counts and poor photon statistics. A discussion of these effects is already presented by Efimov (1968), who estimated lower limits for observational errors in flare star polarimetry.

Flares thus require intense monitoring with a fast polarimeter, simultaneously with photometry and/or spectroscopy, to catch flares with various angles to the line-of-sight. The angular dependence of the polarization could then be determined, and a comparison with theoretical models as the source of polarization could be made. Once the mechanism is well determined, polarization observations will yield important complementary information on the geometry and structure of the flares, and on the magnetic fields in the flares.

The results of broadband linear polarimetry demonstrate, however, that it provides a useful complementary method to support spectroscopic surface imaging (Piskunov, Tuominen, and Vilhu, 1988) of spatial and temporal variations of active regions, i.e., the stellar butterfly diagram. Such simultaneous long term observations may give a method to compare the properties of stellar dynamos with those of the solar dynamo (e.g., Brandenburg and Tuominen, 1988).

Acknowledgements

This work has been supported by the Academy of Finland and the exchange program between the Academy of Finland and The Academy of Sciences of the U.S.S.R.

References

Barbour, M. S. and Kemp, J. S.: 1981, *Astrophys. J.* **246**, 203.
Blanco, C., Catalano, S., and Marilli, E.: 1979, *Astron. Astrophys. Suppl.* **36**, 297.
Brandenburg, A. and Tuominen, I.: 1988, *Adv. Space Res.* **7**, 185.
Bopp, W. B.: 1974, *Astrophys. J.* **193**, 389.
Bopp, W. B., Africano, J. L., Stencel, R. E., Noah, P. V., and Klimke, A.: 1983, *Astrophys. J.* **275**, 691.
Brown, J. C., Mclean, I. S., and Emslie, A. G.: 1978, *Astron. Astrophys.* **68**, 415.
Cassinelli, . P. and Haisch, B. M.: 1974, *Astrophys. J.* **188**, 101.
Chugainov, P. F.: 1980, *Izv. Krymsk. Astrofiz. Obs.* **61**, 124.
Clayton, G. C. and Martin, P. G.: 1981, *Astron. J.* **86**, 1518.
De Jager, C., Heise, J., Avgoloupis, S., Cutispoto, G., Kieboom, K., Herr, R. B. *et al.*: 1986, *Astron. Astrophys.* **156**, 95.
Efimov, Yu. S.: 1968, in L. Detre (ed.), 'Non-Periodic Phenomena in Variable Stars', *IAU Colloq.*, p. 169.
Efimov, Yu. S. and Shakhovskoy, N. M.: 1972, *Izv. Krymsk. Astrofiz. Obs.* **45**, 111.
Eritsian, M. A.: 1978, *Soobshch. Byurakansk. Obs. Akad. Nauk Arm. S.S.R.* **50**, 40.
Ginzburg, V. I. and Syrovatskii, S. I.: 1964, *The Origin of Cosmic Rays*, Mac Millan, New York.
Grinin, V. P. and Domke, H.: 1971, *Astrofizika* **7**, 211.
Huovelin, J., Saar, S. H., and Tuominen, I.: 1988, *Astrophys. J.* **329**, 882.
Huovelin, J., Linnaluoto, S., Piirola, V., and Tuominen, I.: 1985, *Astron. Astrophys.* **152**, 357.
Huovelin, J., Linnaluoto, S., Piirola, V., and Tuominen, I.: 1986, in M. Zeilik and D. M. Gibson (eds.), *Cool Stars, Stellar Systems and the Sun*, Springer-Verlag, New York, p. 333.
Huovelin, J., Piirola, V., Vilhu, O., Efimov, Yu. S., and Shakhovskoy, N. M.: 1987, *Astron. Astrophys.* **176**, 83.
Huovelin, J., Linnaluoto, S., Tuominen, I., and Virtanen, H.: 1989, *Astron. Astrophys. Suppl. Ser.* (in press).
Jetsu, L., Huovelin, J., Vilhu, O., Tuominen, I., Linnaluoto, S., Savanov, I., Shakhovskoy, N. M., and Efimov, Yu. S.: 1989, *Astron. Astrophys.* (submitted).
Joy, A. H. and Abt, H. A.: 1974, *Astrophys. J. Suppl.* **28**, 1.
Karpen, J. T., Crannell, C. J., Hobbs, R. W., Maran, S. P., Moffett, T. J., and Bardas, D. *et al.*: 1977, *Astrophys. J.* **216**, 479.
Kemp, J. C. and Wolstencroft, R. D.: 1974, *Monthly Notices Roy. Astron. Soc.* **166**, 1.
Koch, R. H. and Pfeiffer, R. J.: 1976, *Astrophys. J.* **204**, L47.
Kron, G. E.: 1952, *Astrophys. J.* **115**, 301.
Leroy, J.-L.: 1962, *Ann. Astrophys.* **25**, 127.
Liu, X. and Tan, H.: 1987, *Acta Astron. Sinica* **28**, 39.
Moffett, T. J. and Bopp, B. W.: 1971, *Astrophys. J.* **168**, L117.
Mullan, D. J.: 1975, *Astrophys. J.* **201**, 630.
Mullan, D. J. and Bell, R. A.: 1976, *Astrophys. J.* **204**, 818.
Noyes, R. W., Hartmann, L., Baliunas, S. L., Duncan, D. K., and Vaughan, A. H.: 1984, *Astrophys. J.* **279**, 793.
Pettersen, B. R. and Hsu, J.: 1981, *Astrophys. J.* **247**, 1013.
Pfeiffer, R. J.: 1979, *Astrophys. J.* **232**, 181.
Pfeiffer, R. J. and Koch, R. H.: 1973, *Inf. Bull. Var. Stars*, No. 780.
Piirola, V.: 1973, *Astron. Astrophys.* **27**, 383.
Piirola, V.: 1975, *Ann. Acad. Sci. Fennicae* **AVI**, No. 418.
Piirola, V.: 1977, *Astron. Astrophys. Suppl. Ser.* **30**, 213.
Piirola, V. and Vilhu, O.: 1982, *Astron. Astrophys.* **110**, 351.
Piskunov, N., Tuominen, I., and Vilhu, O.: 1989, *Astron. Astrophys.* (submitted).
Poeckert, R. and Marlborough, J. M.: 1976, *Astrophys. J.* **206**, 182.
Saar, S. H. and Huovelin, J.: 1989, *Astrophys. J.* (submitted).
Shakhovskoy, N. M.: 1965, *Soviet Astron. A.J.* **8**, 833.
Struve, O. and Zebergs, V.: 1959, *Astrophys. J.* **130**, 783.
Struve, O., Herbig, G., and Horak, H.: 1950, *Astrophys. J.* **112**, 216.
Tinbergen, N. and Zwaan, C.: 1981, *Astron. Astrophys.* **101**, 223.
Unno, W.: 1956, *Publ. Astron. Soc. Japan* **8**, 108.
Van Gent, H.: 1931, *Bull. Astron. Inst. Neth.* **6**, 99.
Warwick, J. W.: 1951, *Proc. Nat. Acad. Sci.* **35**, 196.
Weiler, E. J., Owen, F. N., Bopp, B. W., Schmitz, M., Hall, D. S., Fraquelli, D. A., Piirola, V., Ryle, M., and Gibson, D. M.: 1978, *Astrophys. J.* **225**, 919.