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LETTER

Dramatic Spectral and Photometric Changes of Pleione (28 Tau) between 2005 November and 2007 April

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Abstract

Recent photometric and spectroscopic observations of Pleione are reported. Pleione showed brightness declines in both the B and V bands by $\sim 0^{\mathrm{m}}.25$ between 2006 January and 2007 March. Significant decreases in the strengths and widths of the long-lived emission components in Hα and Hβ were observed during this period, while additional outer double-emission components appeared in these lines. Many metallic shell lines strengthened during the observation period, being accompanied by central quasi-emission components. We interpret these spectral changes in terms of a double disk: the progressive decline of a misaligned old disk in due course of precession and the formation and growth of a new disk in the star's equatorial plane.

Key words: Stars: atmosphere — Stars: Be — Stars: emission line — Stars: individual: 28 Tau — Stars: photometry — Stars: spectroscopy

1. Introduction

Pleione (28 Tau, HD 23862) is a B8Vpe star (Hoffleit & Jaschek 1982) and a member of the Pleiades cluster. It is known to exhibit prominent long-term photometric and spectroscopic variations with a period of about 35 yr. A comprehensive summary of observations of Pleione is given in Hirata (1995). In the recent 70 years, Pleione showed a cyclic change twice between a Be-shell phase and a Be phase. In the recent 35-year cycle, it entered a Be-shell phase in 1972, initiated by the appearance of a wide and shallow absorption of the Ca II K line (Gulliver 1977). Then, the star developed many shell absorption lines in its spectrum. At the same time, the star had shown a decrease in its brightness, beginning at the end of 1971. After reaching the minimum brightness in late 1973, with a total drop of $\Delta V \sim 0^{\mathrm{m}}.5$, the star gradually brightened. In 1989, Pleione entered a Be phase and stayed as a Be star until the summer of 2005.

Pleione is known to be a speckle binary (McAlister et al. 1989), although its orbital parameters have not yet been established. Katahira et al. (1996) found that Pleione is a single-lined spectroscopic binary with an orbital period of 218.0 d and a large eccentricity of $e = 0.6$.

Recently, Hirata (2007) reported the result of his long-term polarimetric observations of Pleione, and found that the intrinsic polarization angle had varied from 60° to 130° during the period 1974–2003, which provided direct evidence for a spatial motion of the disk axis. This was the first finding among Be stars based on polarimetric observations. He interpreted this fact in terms of disk precession caused by the secondary of the spectroscopic binary. The precession period is 80 yr. This type of misaligned (or tilted) disk was first proposed by Hummel (1998) as an interpretaion of spectacular spectral changes observed in 59 Cyg and γ Cas.

By adopting a period of the activity cycle of ~ 35 yr from the star's past behavior, the beginning of the next phase was expected to occur in late 2006 or early 2007. However, we found a wide and shallow absorption of the Ca II K line on a spectrum obtained on 2005 December 15 (Katahira et al. 2007). Gulliver (1977) concluded that the appearance of the broad component of the Ca II K line is a precursor of new shell activity. Hirata (1995) suggested that this component is formed in the interface region between the photosphere and the disk. Being stimulated by the above finding, which was about one year earlier than the expectation, we initiated intensive photometric and spectroscopic monitoring observations of Pleione in 2006 January. The results of observations at Nishi-Harima Astronomical Observatory (NHAO) and at Osaka Kyoiku University until the end of 2007 April are reported in this short paper.

2. Observations

2.1. Photometric Observations

Johnson UBV photometric observations at NHAO were carried out on four nights between 2006 January and 2007 March, using a 60 cm Cassegrain reflector. A photon-counting photometer (AES/PCPA2) was used. A nearby star, 27 Tau, was used as a reference star on 2006 January 9, and 19 Tau was used as a reference on the remaining three nights. We had

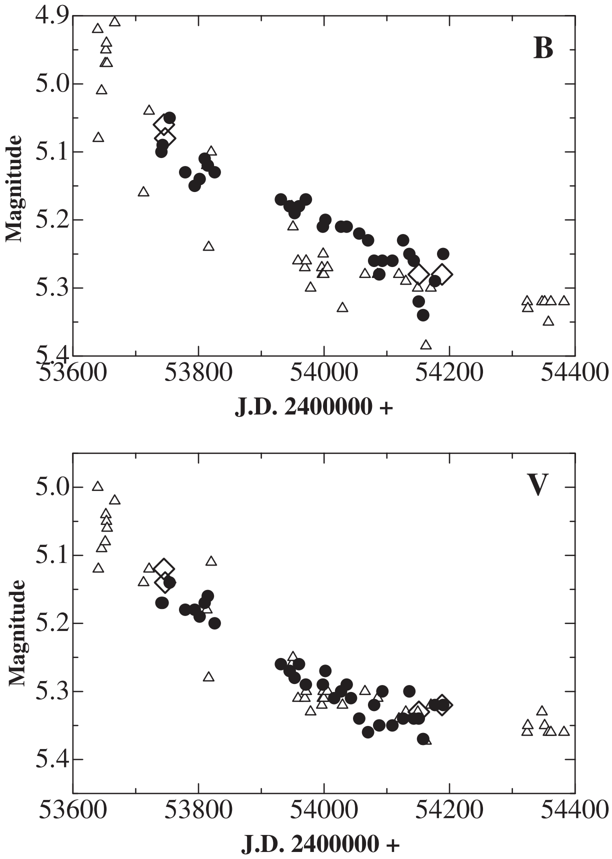

Fig. 1. Photometric variations of Pleione from 2005 to 2007. Data of the B and V bands are shown in the upper and lower panels, respectively. The filled circles and open diamonds represent data obtained at Osaka Kyoiku University and at Nishi-Harima Astronomical Observatory, respectivly. The open triangles show 1971–1973 data of Sharov and Lyutyi (1992) shifted by 34 yr.

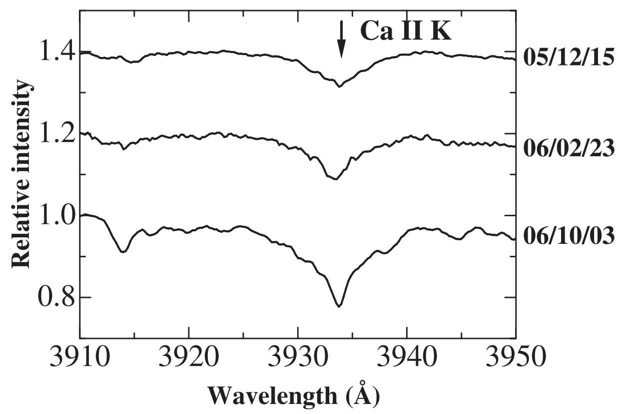

Fig. 2. Evolution of the Ca II K line from 2005 December to 2006 October.

switched from 27 Tau to 19 Tau because the former might be a variable star with a small amplitude of $\sim 0^{\mathrm{m}}\!.003$ (McNamara 1985). No check star was observed. CCD photometric observations of the B and V bands were carried out at Osaka Kyoiku University using a 51 cm Cassegrain reflector and a LN2-cooled CCD camera. Observations were made on 34 nights between 2006 January and 2007 March. A nearby star, 27 Tau, which is the only bright star in the same field of view ($15' \times 10'$), was used as a reference star. In order to reduce the bright incident light from these stars and to obtain CCD images without saturation, we placed a pin-holed cap at the top of the telescope tube. Measurements of the instrumental magnitudes were carried out by using the aperture photometry routine APPHOT in IRAF. The B and V magnitudes of Pleione were determined differentially relative to 27 Tau, for which we used $B = 3.54$ and $V = 3.62$.

The resulting light curves in the B and V bands are shown in figure 1. Data of 1971–1973 taken from Sharov and Lyutyi (1992) are shown for comparison after shifting by 34 yr. We found that both the B and V maginitudes were $\sim 0^{\mathrm{m}}\!.1$ fainter than the normal state [$B = 4.95 \pm 0.05$ and $V = 5.05 \pm 0.05$, Sharov & Lyutyi (1992)] at the beginning of our observations in 2006 January. By assuming a linear declining rate of $0^{\mathrm{m}}\!.025$ per month in the V band, we guessed that the decline had started between 2005 August and October. In 2006 January, a private communication was provided from V. M. Lyutyi, who noted that the decline had actually begun in 2005 September.

2.2. *Spectroscopic Observations*

The spectroscopic observations of Pleione reported in this paper were carried out using a spectrograph installed on the Nasmyth platform of the 2 m NAYUTA telescope at NHAO. The spectrograph is equipped with a 2K$\times$2K CCD detector (13.5 μm pixel), by which a 400 Å region can be observed at a resolving power of $\sim$ 7000 in a single exposure. Technical details of the spectrograph are given in Ozaki and Tokimasa (2005). Our first observation was carried out on the night of 2005 November 15 in the Hα region. The Hα observations were made on nine nights until 2007 April 28. Observations in the Hβ, Hγ, Hδ, and the Ca II K line regions were carried out on 16, 9, 5, and 3 nights, respectively, during the above period. Typical exposure times were 300–500 s. The reduction of two-dimensional spectral data (bias subtraction, flat-fielding, scattered-light subtraction, extraction of spectral data, and wavelength calibration) was performed using the IRAF software package in a standard manner. The wavelength calibration was performed using Fe-Ne-Ar lamp exposures obtained during the observations. The typical SN ratio (per resolution element) of the resulting continuum rectified data was around 600 near Hβ.

Evolution of the Ca II K line, which is known to be a precursor of a new shell activity cycle (Gulliver 1977), is shown in figure 2. It became deeper and wider within one year. Figure 3 shows the spectral variation in the Hα region from 2005 November to 2007 April. We notice that the peak intensity of the emission decreased from 3.8 to 1.8 of the continuum level, and the total width (TW, measured at the bottom of the sharp emission components) decreased significantly between 2005 November and 2006 October. Figure 4 shows the variation in the Hβ region from 2005 December to 2007 April. The peak intensity of the Hβ emission was 1.3-times higher than the continuum in 2005

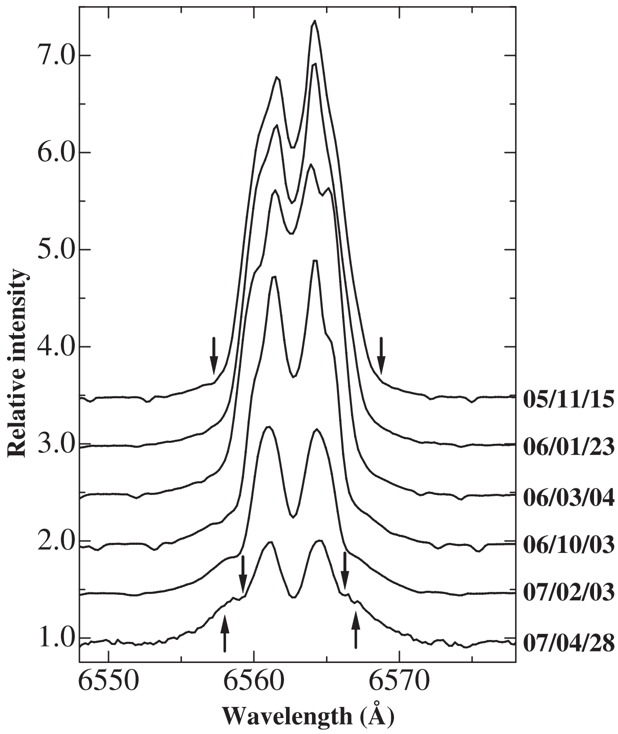

Fig. 3. Evolution of the profile of Hα from 2005 November to 2007 April. Emission components coming from the new disk are indicated by upward arrows. Downward arrows show the positions of TW measurements.

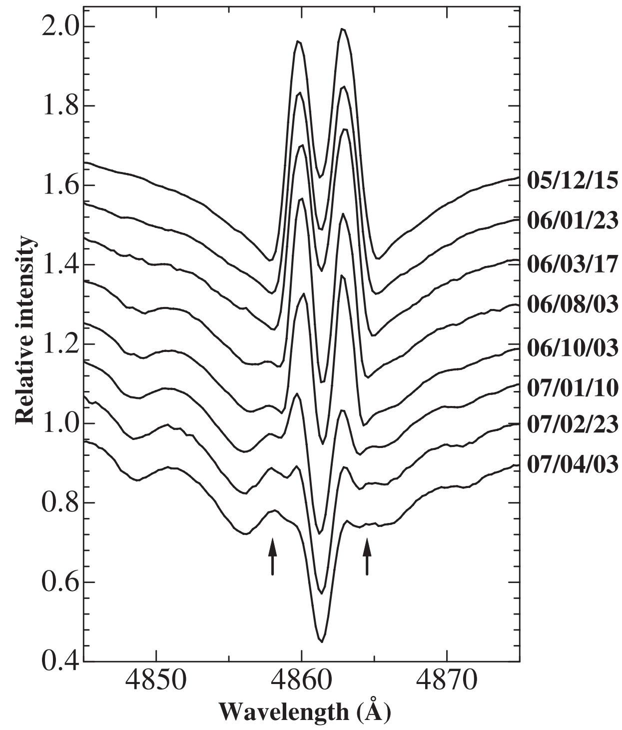

Fig. 4. Evolution of the profile of Hβ from 2005 December to 2007 April. Emission components coming from the new disk are indicated by upward arrows.

December. The double-emission components weakened with time, and became much fainter by the end of 2007 March. Figure 5 shows time variations of the measured total width of both the Hα and Hβ emission lines. Both emission lines had TW $\sim 500\,\mathrm{km\,s^{-1}}$ at the end of 2005, while the TW became as small as $\sim 300\,\mathrm{km\,s^{-1}}$ in 2007. Since the time interval of our observation (1.5 yr) was very short compared with the precession period of 80 yr, we may assume a constant inclination angle for the disk. The considerable decrease in the TW indicates an increase of the inner radius of the disk. Our observations clearly show that the disk had lost a significant part of its inner part during the observation period.

We further noticed an emergence of a pair of new emission components (indicated by arrows in figures 3 and 4) outside the narrow double emission components of Hβ in 2006 August and Hα in 2007 February. We interpret these new components as having originated in an inner disk, which had been newly formed by gas ejected from the equator of Pleione.

We also found a rapid growth of metallic shell-absorption lines, which were not visible during the Be-phase. The time evolutions of the two singly ionized metallic lines, Ti II 4805.089 Å and Cr II 4824.127 Å, are displayed in figure 6, while those of two neutral Fe I lines, 4045.812 Å and 4063.594 Å, are shown in figure 7. All of these absorption lines were wide and shallow at the beginning (2005 December) and showed weak central quasi emission features (CQE). These lines grew narrower and deeper with time. The widths of CQE became narrower, and finally disappeared in an observation on

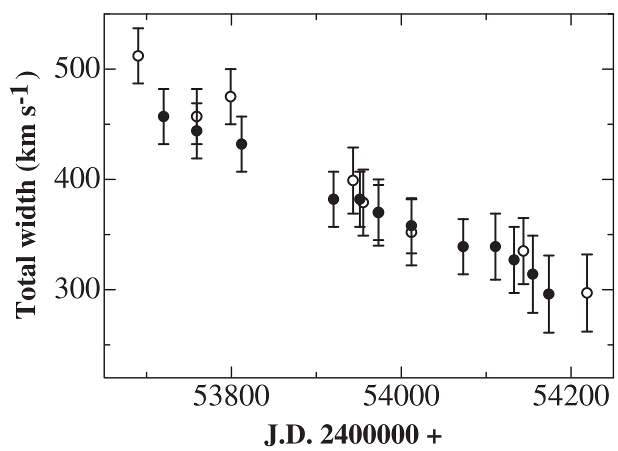

Fig. 5. Changes in the total width (TW) of Hα (open circles) and Hβ (filled circles).

2007 January 10. This behavior of the CQE corresponds to the growth of a new disk, as discussed in Hanuschik (1995). Our detection of the Fe I lines implies that the new disk is relatively cool when compared with the temperature of the photosphere. From these observations, we conclude that we were observing both the decaying process of the old disk and the growing process of the newly formed disk during the period from 2005 November to 2007 April.

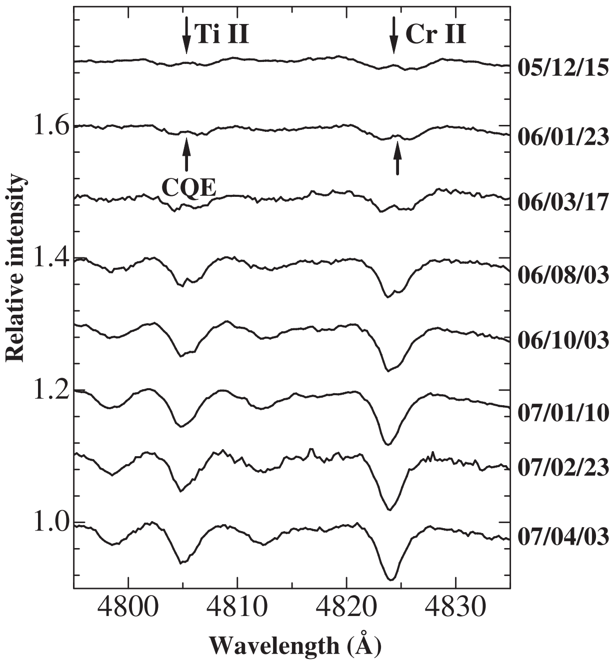

Fig. 6. Evolution of shell absorption lines of Ti II 4805.089 Å and Cr II 4824.127 Å from 2005 December to 2007 April. The upward arrows indicate the central quasi emission (CQE) components.

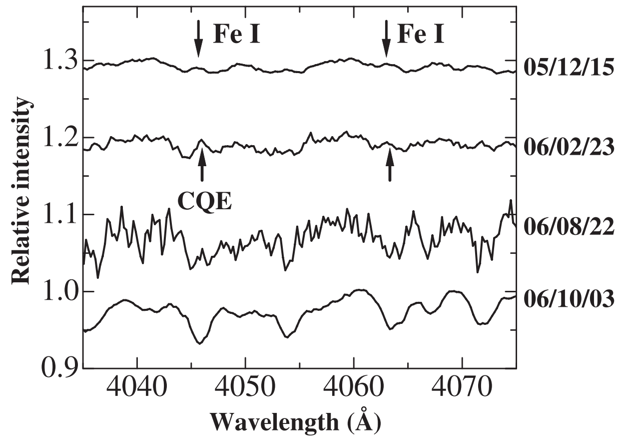

Fig. 7. Evolution of shell absorption lines of Fe II 4045.812 Å and 4063.594 Å from 2005 December to 2006 October. The upward arrows indicate the CQE components.

3. Discussion

From frequent photometric and spectroscopic observations of Pleione during 2005 November and 2007 April, we found remarkable changes in both the brightness and the profiles of the Balmer and metallic lines. The development of a wide and shallow profile of the Ca II K line clearly showed the beginning of a new activity cycle in the latter half of 2005, which just coincides with the beginning of the observed photometric changes. It is natural to imagine that the new disk was formed in the equatorial plane, and we assume that the effect of precession to the new disk was negligibly small during the short time interval (1.5 yr). Then, observations of a pair of new emission components in both Hα and Hβ and the developments of metallic shell absorption lines accompanied by CQE demonstrate the formation and growth of a new disk in the equatorial plane of the star. At the same time, weakening profiles of the Balmer lines show that the old disk, which was formed in 1972, was decaying, but still existed until 2007 April, more than one year after the formation of the new disk.

Evidence for a double disk has been reported in several Be stars [X Per: Kunjaya & Hirata (1995), Tarasov & Roche (1995), Clark et al. (2001); μ Cen: Rivinius et al. (1998, 2001); 28 CMa and FV CMa: Rivinius et al. (2001)]. A double disk is expected to be formed when a new outburst begins before a disapperance of the old disk. Such a case is highly probable in the Keplerian disk, because the decay of the old disk after termination of the mass supply proceeds in a viscous timescale on the order of ten years (Okazaki 2007). In the case of a hot Be star X Per (HD 24534, known as a Be/X-ray binary system), the polarimetric observations showed that the variation on the (q–u) plane lies on a straight line (Kunjaya & Hirata 1995; Roche et al. 1997). This suggests no disk precession or the precession period much longer than the activity timescale. Thus, we conclude that the double disk in X Per is essentially coplanar.

However, in the case of Pleione, Hirata (2007) showed that the disk of Pleione had experienced a very large precession during the past 30 years. His calculation indicates that the inclination angle of the central star is 60° and the inclination angle of Pleione's old disk was around 30° in 2005–2007. Assuming the new disk was ejected from the star's equator, we can suppose that two disks locate in the above configuration.

Such a misaligned double-disk structure has so far never been observed among Be stars. Thus, Pleione provides a rare opportunity to investigate the forming process of a new disk and the interaction between the two disks. More detailed analyses of the development of the new disk and the decay of the old disk will be carried out based on higher resolution spectral data, and will be reported in a forthcoming paper.

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