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Short-Term Variability of Hα Emission Line Parameters in π Aqr as a Be Star

Taufieq Zannata Ramadhan[1,*], Aprilia[2]

[1] *Astronomy Study Program, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Jl. Ganesa No. 10, Bandung, 40132, Indonesia*
[2] *Astronomy Research Group, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Jl. Ganesa No. 10, Bandung, 40132, Indonesia*

*Corresponding Author Email: taufieqzannataramadhan@gmail.com

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ABSTRACT

B-emission (Be) star is a B type star which shows emission line in its spectrum, especially Hα, caused by the disk surrounding it. One of the Be stars, π Aqr, is a binary Be star in constellation Aquarius which shows variability of double-peaked Hα emission line caused by a circumstellar disk around the primary component. We aim to study recent physical phenomenon which occurs in the disk of π Aqr star based on its spectral data from 2004 to 2024, retrieved from BeSS database, by analyzing the variability of its Hα emission line parameters: the Violet-to-Red peak ratio (V/R), Emission-to-Continuum ratio (E/C), Equivalent Width (EW), Full Width at Half Maximum (FWHM), and peak separation. The variation of V/R ratio from 2004 to 2019 shows period of 84.1 days which corresponds with orbital period of the binary system. However, in 2024, the V/R variability does not show similar cycle period in previous years as the red peak strength dominates throughout most of the year. The EW and E/C increase, indicating rising disk activity and expansion until 2024. Overall increase of red and blue peak separation roughly suggests expansion in Hα region in the disk.

Keywords: Be star, π Aqr, spectrum variability, line parameter, circumstellar disk

INTRODUCTION

Be star is a B-type star which shows bright or emission line in its spectrum profile. This emission line usually appears in a shape of single peak, double peak, or shell. Different emission line shapes could be affected by disk inclination [1]. In general, emission line of a Be star is known to show variability over time with different period [2-3]. One of the Be star, π Aquarii or π Aqr, is a binary star system that is located in constellation Aquarius. Based on spectroscopic observation, only the primary component is classified as a Be star since its spectra show emission line profile, especially in Hα wavelength. The emission line is caused by disk-like structure consists of ejected matter from the primary star that surrounds and rotates around it.

As a binary star, π Aqr shows the spectrum profile of π Aqr was stated as double peak which consists of violet (left) and red (right) peak [4]. As discovery made by Slettebak [5] and Bjorkmann and Miroshnichenko [6], the primary star is a B1III-IVe type star with mass around 11 ± 1.5 $M_\odot$, radius around 6.1 ± 2.5 $R_\odot$, and effective temperature around 24000-25000 K. The primary star rotates quite fast with the rotational velocity ($v \sin i$) around 300 km/s, as stated by Bjorkmann and Miroshnichenko [6]. The secondary star is an A or F type white dwarf star that orbits the primary star in inclination of 50°-75° with an orbital period of 84.1 days. The secondary star is a white dwarf star with mass less than 1.4 $M_\odot$ [7].

Discussions regarding short term variability of emission profile of π Aqr have existed for a long time. According to record of Mclaughlin [8], in 1911-1960, π Aqr showed variation in Hβ dan Hγ emission line V/R parameter. From 1950s, Hα emission line strength and brightness of π Aqr increased until reached its peak in around 1980-1985, shown by its equivalent width, polarization, and photometry data [6]. From 1973 to 1989, in the time of strengthening of its emission line, the emission profile was in single-peaked shape. After 1985, the emission line strength and brightness gradually decreased until it reached its minimum value in 1995 [6]. While weakening of emission line occured, in 1989, the emission line profiles simultaneously changed from single peak to double peak [9]. Based on this event, from 1995, Bjorkmann and Miroshnichenko [6] believed that π Aqr nearly lost its disk and entered “quasi-static Be star phase”. After that, the spectrum profile show emission line which currently still exist.

π Aqr has undergone some various variations related to emission line profile and could possibly happen again in the future. This particular variability detected from π Aqr captures our interest to study about its recent emission line variability and the occuring phenomena which affects it even further. In this work, we study variability of Hα emission line profile of π Aqr from 2004 to 2024 by analysing its spectral lines parameters which consists of Violet-to-Red intensity ratio (V/R, ratio of height of both peaks that is caused by radial movement of envelope), Emission-to-Continuum intensity ratio (E/C, height of each peak), Full Width at Half Maximum (FWHM), equivalent width (EW), and the separation between the two emission peaks. We aim to show the recent variability of its emission line profile, emission line parameters, and relation between the variability of emission line parameter to one another to study the physical phenomena which might occur in its disk using current spectral data of this star.

METHODS

Data

The spectral data used in our work is from HJD 2453273 to 2460620 which corresponds to 24 september 2004 to 6 November 2024. The spectral data are retrieved from BeSS database [10] which is managed by LESIA Laboratory of the Observatoire de Paris-Meudon. Bess catalogue provides spectral data from amateur or professional astronom using various instruments. For this work, we use high resolution data captured from telescope with resolution of around R~15000-30000 and only focus on Hα emission line so the spectral line profiles are only limited in wavelength around 6560 Å.

Method

We normalize the continuum line of each spectrum and thus set the continuum level across the whole spectrum profile to 1. In the nest step, we deblend the spectrum which basically pick which area of the emission line to be fitted. Following this, the data were subsequently fitted with Gaussian or Voigt distributions to extract the necessary parameters for this analysis, namely E/C (ratio between intensity of each emission peak and continuum line), V/R (ratio between intensity of each peak), EW (strength of a spectral line which is defined as the width of a rectangle at the continuum level that has the same area as the emission feature) which shown in negative sign, FWHM (the line width at half of its intensity), and peak separation. We conduct both spectrum normalization and fitting process using IRAF software [11]. FWHM and peak separation unit first should be converted to km/s unit using Doppler equation:

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta V}{c}, \tag{1}$$

with Δλ is the FWHM in Å unit, λ is Hα emission wavelength, c is light speed, and ΔV is FWHM in km/s unit. Both peak separation distance in wavelength is used to determine radius of emission line forming region using equation

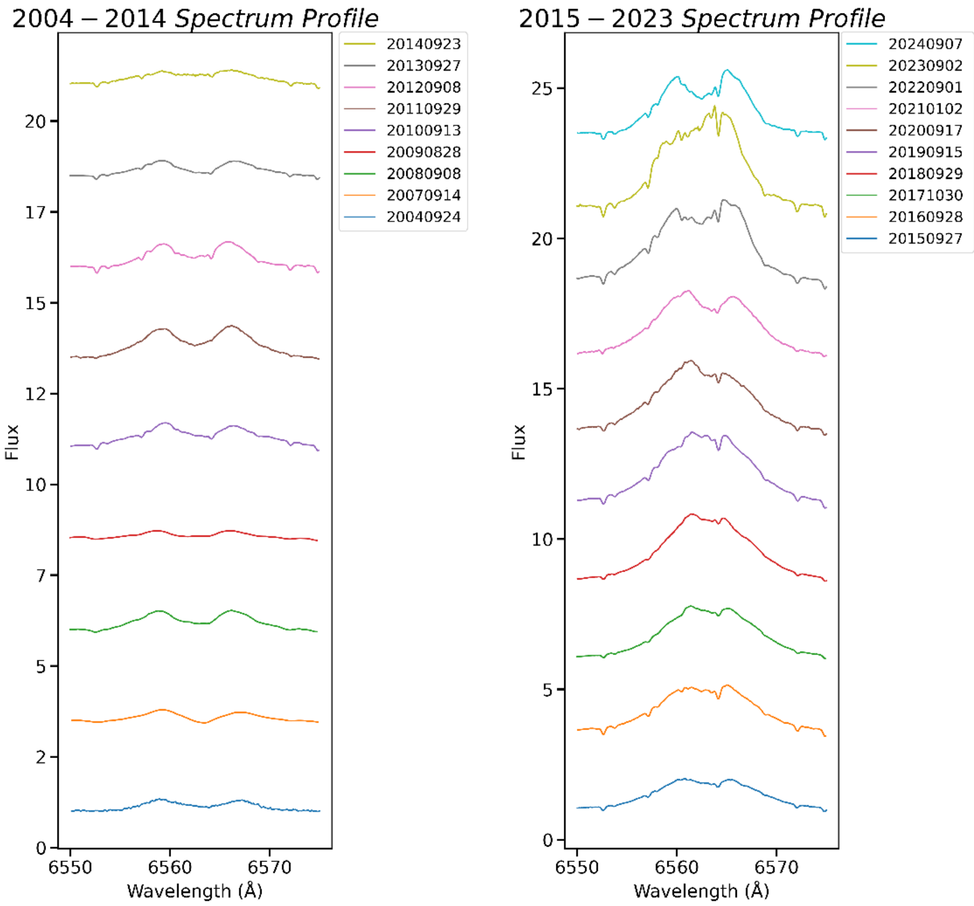
$$\frac{R_d}{R_*} = \left(2\frac{v \sin i}{\Delta V}\right)^{1/j}, \tag{2}$$

with R_d is emission source region radius in the disk, R_* is the star radius, v sin i is star rotational velocity, and j is constant, with j = 0.5, as the envelope "orbits" around the star in Keplerian motion [12].

RESULTS AND DISCUSSIONS

Variability of Spectrum Profile

Strength of the emission line constantly grow until 2024 with noticeable drops in 2009 and 2014. This emission line weakening was also recorded by Nazé et al. [13]. From 2004 to 2014, the general shape of the emission line profile was double-peaked. The shape began to shift and was dominated by single peak from 2015 until 2023 eventho some emission line profiles still show double-peaked shape. The emission profile subsequently turn into double peak again in 2024, as shown in FIGURE 1. Transformation between emission line profile from single to double peak has also occurred in 1989 [6].



(a) (b)

FIGURE 1. (a) Hα spectrum profile variability from 2004 to 2014 shows double-peaked shape. (b) Hα spectrum profile variability from 2016 to 2023 is dominated by single peak emission line shape. Then, in 2024, emission line turn into double peak again with deeper center absorption line.

Variability of Emission Line Parameters

Emission-to-Continuum and Equivalent Width

Here we use E/C and equivalent width (EW) parameter to measure strength of emission line. E/C shows height of each emission line peak while EW explain how large the emission line is. We use both parameter as equivalent width alone is not enough. This happen because in some the case of other Be star, for example α Eri, emission strengthening could be balanced by deepening of the absorption component. Thus, equivalet width would appear constant despite change of its strength [14].

All Hα spectrum profiles show emission line. Thus, measurement of EW and E/C could indicates expansion or dissipation of the envelope disk [15]. FIGURE 2 shows pattern of E/C line parameters which are separated for each violet and red peak. Overall, both peaks keep increasing until 2024, which also means the emission line is constantly getting "taller". However, from HJD 2456105 (June 2012) to HJD 2456893 (August 2014), the E/C parameter shows a noticeable decline, approaching nearly zero, followed by a steady increase leading up to 2024. This was also recorded in previous work regarding this star [13, 16]. After HJD 2459591 (January 2024), the emission strength shows signs of weakening as shown by the decreasing E/C ratio until late 2024. This could be an indication of dissipation phase of the disk.

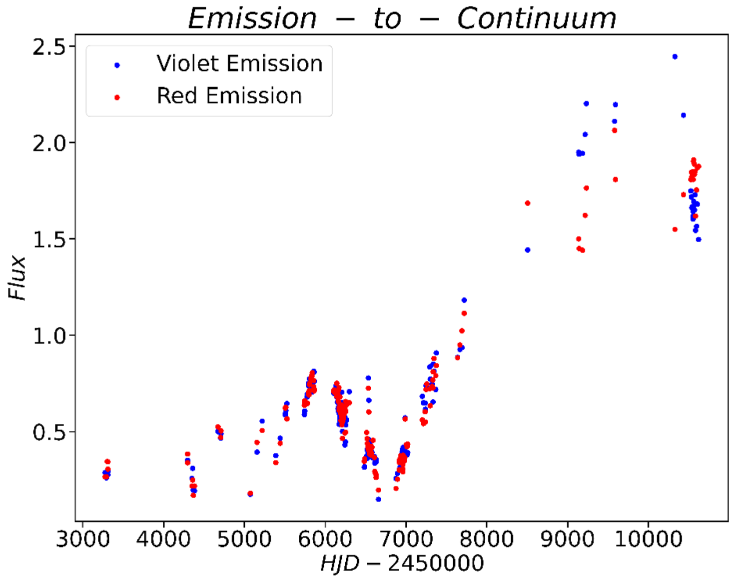


FIGURE 2. E/C line parameter variability from 2004 to 2024. Both peaks keep increasing until 2024. However, from 2012 to 2014, the E/C parameter decreases which subsequently increases until 2024.

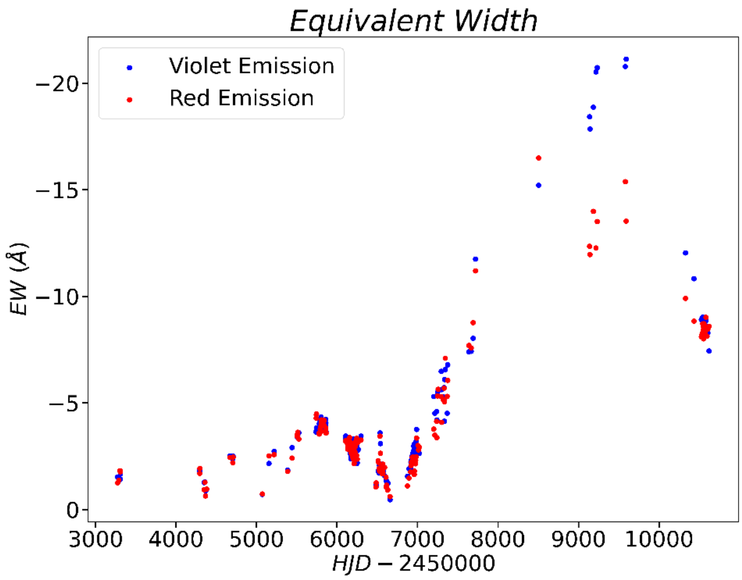


FIGURE 3. Equivalent Width (EW) variability from 2004 to 2024. EW shows more or less similar pattern wth E/C until 2024.

FIGURE 3 shows almost similar data pattern between EW and E/C line parameters. EW shows increase from 2004 to 2024 which means the emission line is basically getting "larger", most likely caused by outburst of ejected material from the primary star. There is also a noticeable drop in HJD 2455858 (October 2013) which also detected by previous work until almost reaching zero [13, 16]. After HJD 2459591 (January 2022), EW gradually declines. Current increasing of EW is suspected to resemble the one observed in 1970-1985 [6] which suggests a recurrence of similar physical activity in the disk of π Aqr.

Full Width at Half Maximum

The FWHM parameter explains width of half of emission height. In FIGURE 4, emission line for each peak is gradually narrowing from HJD 2458505 (January 2019) after it shows almost similar variability with E/C and EW parameters. The primary star most likely stop ejecting material to the disk after the outburst, causing the FWHM to gradually narrowing as the material ejected move outward to the outer part of the disk. The similar case also recorded in Be star HD 6226 [17], where the FWHM is gradually narrowing after this star shows outburst event which is indicated by maximum value of equivalent width of Hα and Hβ emission line.

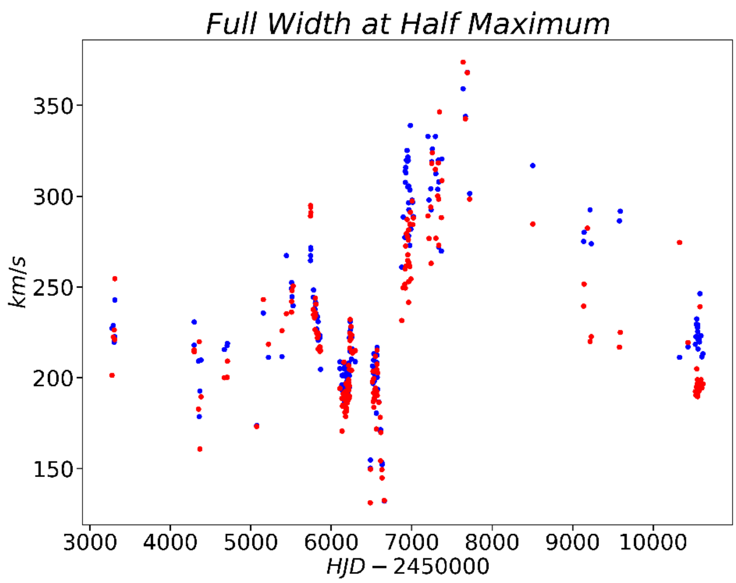
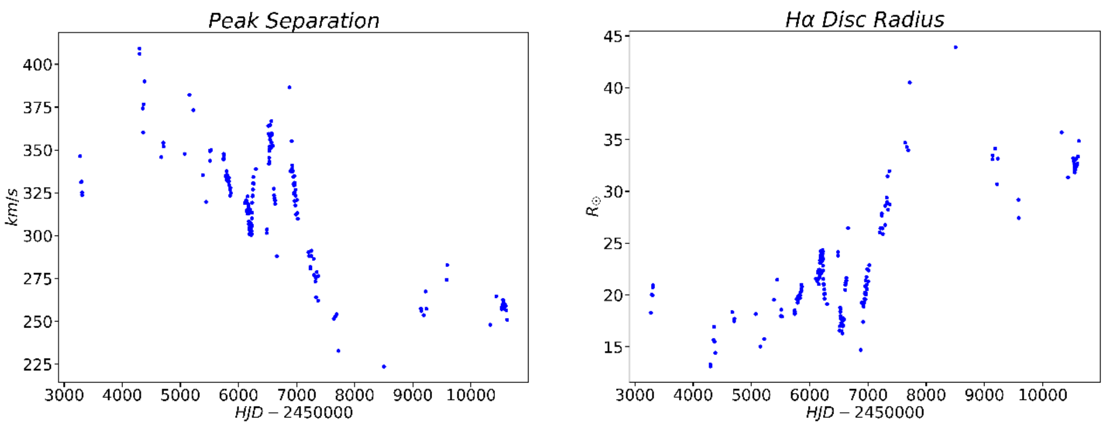


FIGURE 4. FWHM variability from 2004 to 2024. Emission line keeps narrowing from 2019 after it shows almost similar variability with both E/C and EW parameters.

Peak Separation

We use the peaks separation data to determine the radius of Hα emission line forming region using Equation (2). Data plot of peaks separation and radius of emission line forming region in the disk are shown in FIGURE 5. Measurement of peak separation could show outer radius of region in the disk which is the source of emission line. Both data shows opposite trend which is consequence of the inverse relationship between these data as defined in EQUATION (2). Data plot of emission line forming region radius presented in FIGURE 5 shows similar pattern with E/C and EW which further support our hypothesis that outer radius of the emission line forming region in the disk, and allegedly the whole disk, keep expanding. In late 2020, peak separation stops declining and we suggest that disk expansion gradually begun to cease.



(a) (b)

FIGURE 5. (a) Violet and red peaks separation distance variability data from 2004 to 2024. (b) The radius of Hα emission line forming region from 2004 to 2024, which is shown in solar radii units.

Violet-to-Red Ratio

V/R parameter explain height or strength difference of violet and red peak. This strength difference is caused by asymmetric density distribution where there is one denser side of the disk that rotates around π Aqr primary star [18]. Its radial movement cause peak strength difference. We phase-fold the V/R variabilty from 2004 to 2019 and we show it in FIGURE 6. From 2004 to 2019, V/R ratio periodically fluctuates in a cycle with periode of around 84.1 days which corresponds to orbital period of the secondary component [6]. This also quite the same with previous work from [16]. This could be indication of possible influence from secondary star on the variability of the V/R parameter. However, from 2016 to 2023, emission line shape is dominated with single peak as previously shown in FIGURE 1. Therefore, the V/R variability cycle is quite difficult to identify.

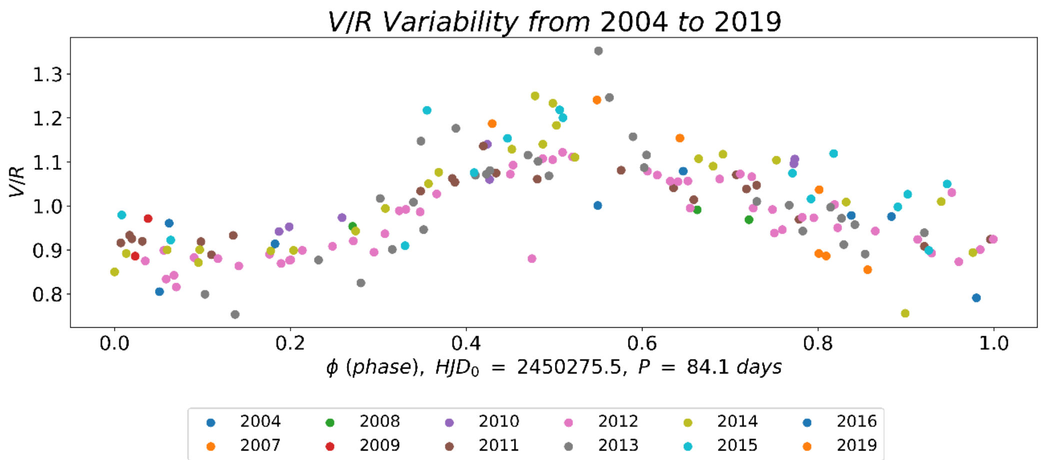


FIGURE 6. Phase-folded V/R variability from 2004 to 2019 shows V/R cycle with period of 84.1 days.

In 2024, the emission line profiles once again show double-peaked shape but with different V/R variability. As shown in FIGURE 7 and FIGURE 8, value of V/R almost constantly less than 1 as red peak appears to be stronger most of the time. Eventho its emission line profile return to double peak, V/R variability cycle remains irregular, with the cycle suggested to be longer or even no longer exists. Unfortunately, the lack of spectral data make drawing conclusion from this anomaly quite difficult. FIGURE 8 presents emission line profile throughout 2024 which is dominated by double-peaked emission line.

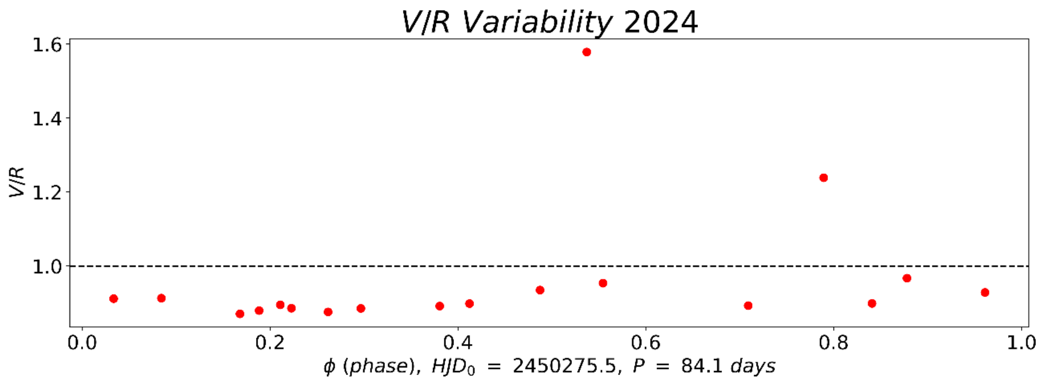


FIGURE 7. V/R variability in 2024. Emission line shape turn to double peak again. In 2024, however, V/R does not show similar period with previous years. Most of the V/R is less than 1.

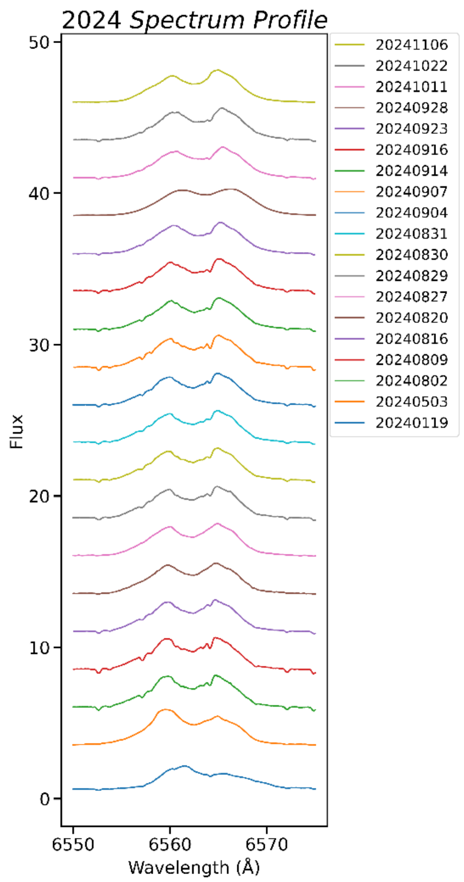


FIGURE 8. Emission line shape in 2024. Emission line profiles have turned back to double-peaked shape. Most emission profiles show stronger red peak than violet peak.

Discussion

This star once again shows an increasing disk activity similar to what have occurred until early 1980s. When the emission line strength of π Aqr peaked between 1980 and 1985, the emission line profile is in single peak shape [6]. Following this, in 1989, the profile changed from a single peak to a double-peaked structure and accompanied by gradual decrease of emission line strength until reached its minimum in 1995 [6].

In Based on the variability of its emission line parameters, as well as the change of emission line profiles, π Aqr exhibited this similar type of variability in 2004-2024 which in this period it shows strenghening of emission line. The emission line strength keep increasing from 2004 and reach its peaked around 2022 as seen from the equivalent width and E/C parameters which most likely shows outburst of material ejection from primary star to the disk. The profile was dominated by single peak shape. This was followed by gradual decline of emission line strength until late 2024, along with a transition in the emission profile from single-peaked to double-peaked shape. Increasing in activity may indicate expansion of the disk as shown by positive trend of EW, E/C, and peak separation in its Hα emission line. As the emission line reach its peak and gradually weakening in 2022-2024, we suggest this disk expansion might gradually begun to cease. Change of equivalent width also recorded in some Be stars cases which indicate disk expansion and rising disk activity, including outburst. Hanuschik et al. reported that μ Cen star is in the middle of building a new permanent disk as shown by appearance of emission and its increase of E/C [19]. Rivinius et al. also report strengthening of emission line of Paschen line during that μ Cen outburst in 1995 and 1996 [20]. Sejnova and Votruba also report assumed change of circumstellar disk size from 60 Cyg as shown by strengthening and weakening of its equivalent width from 1992 to 2006 [21]. Same case also reported for alpha eridani (Achernar) [14] which shows disk formation phase from 2002 to 2006 interpreted from its emission line strengthening.

Data from the Hα emission line region also show the increase of Hα emitting region radius in the disk. This rising envelope activity accompanied by an expansion of the circumstellar envelope around π Aqr. The FWHM data have shown a declining trend after it gradually grows which implies gradual narrowing of the emission line most likely caused by the disk no longer receive ejected material from primary star after outburst. Its variability also resembles variability of measured Hα this radius (FIGURE 5.b).

As a binary Be star, π Aqr shows similar period between the secondary star orbit and the primary disk V/R variation. This is commonly known as 'V/R variation phase-locked'. Miroshnichenko et al. reported 12 binary Be star system with V/R variation that phase-locked with its orbital period [22]. Tidal interaction between the primary and secondary stars in the π Aqr system could be the cause of this phenomenon [23].

Furthermore, the V/R variability from 2004 to 2019 reveals a repeating cycle with a period of 84.1 days. This period is consistent with the orbital period of the secondary star which suggests a possible direct role of the secondary in modulating the variability of the V/R intensity ratio. However, by 2024, the V/R variability cycle is no longer observed. There is a possibility that the cycle period of V/R variability might become longer compared to observed period in 2004.

CONCLUSION

Previous research regarding π Aqr emission line variability and this work indicates that π Aqr might have undergone a cycle of increasing and decreasing activity in its envelope. After reaching the maximum value of emission line strength in 2022, decreasing of emission line strength throughout 2024 is accompanied by shift of emission line peak shape from single to double. There are three events occurring simultaneously at the same time that appear to be connected: emission line strength increases constantly until reach its maximum value which shows increasing activity in π Aqr disk (outburst), expansion of the disk, and emission line profile change. The mentioned events have occured around 50 years ago and show possibility of reoccurence of the same physical acitivity. However, further observation data is necessary to draw such conclusion.

The V/R variability cycle shows similar period with the secondary orbital period. However, in 2024, the V/R ratio no longer shows a detectable cycle with the same period. Further observation is necessary to check whether the V/R cycle period of this star has truly changed or if it occurred only during this specific time. Further observation data and high cadence observation are also necessary to determine whether emission line weakening which we area witnessing continues, thus conclude the emission-line variability seen in 1980s ago has reappeared. We also suggest to study this star through different spectrum wavelength to study occuring event in different region of the disk. We also suggest to study this star through different approaches, especially photometry, to confirm the outburst event.

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