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Continuum energy distribution and photometric behaviour of π Aqr

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Summary. New observations of π Aqr in the optical and infrared (IR) region are presented. The effective temperature of π Aqr is derived by comparing observed and computed fluxes in the optical region. No near-ultraviolet excess was found but a strong near-IR excess beginning at λ5500 Å and extending to longer wavelengths was detected. Two separate IR excess emission peaks of variable strength have been distinguished.

By combining the present observations with the previous available data it is shown that π Aqr has a long-term variation of brightness and exhibits variation of type I. It is proposed that the variable dimension and density of the circumstellar (CS) envelope resulting in a variable amount of excess continuous hydrogen emission is responsible for such light variations.

1 Introduction

The Be star π Aqr (HR 8539, HD 212571) has variously been classified as B0Ve, B1Vep, B1nnek, etc. The spectral variations of π Aqr during the period 1911–61 have been thoroughly described by McLaughlin (1962). Cester *et al.* (1977) announced that this star was almost certainly variable at Hα, based on a comparison of photometric observations made during 1961–63 and 1973–76.

On the shorter time-scales, Gray & Marlborough (1974) found night-to-night variations in Hα. Fernie (1975) also found photometric instability and suggested pulsation as the cause. Fernie observed no great degree of variation (night-to-night) in π Aqr, although variations of up to 0.03 or 0.04 mag were noticed.

On the other hand, Haefner, Metz & Schoembs (1975) made simultaneous observations of π Aqr with high time resolution during 1973 October 26–30 and found no strongly significant variations within time-scales of minutes to days. Slettebak & Reynolds (1978) found no striking Hα profile changes during 1975 December and 1976 November, on time-scales of one day. No changes in equivalent width, radial velocity and line profile in the Hα emission of π Aqr over time-scales of several hours have been found by Fontaine, Lacombe & Wesemael (1983) during 1982 August 29 and 30.

Nordh & Olofsson (1977) reported, from intermediate-band photometry for spectrophotometric purpose, no continuum changes larger than the dispersion in the measurements (0.01 mag) during the time of observations in 1972 June. Recently, Ashok *et al.* (1984) found no variability in IR magnitude (*JHK*) of π Aqr during 1980 October. In order to study the nature of the star and its variability, we present simultaneous spectrophotometric (in the optical region) and IR photometric (*JHK*) observations. When compared with previous observations of π Aqr it is found that this star has a long-term variation in brightness.

2 Observations

The spectrophotometric observations in the optical region ($\lambda\lambda$3500–7500 Å) were made on 1980 September 27 and 30 with the 52-cm reflector of the Uttar Pradesh State Observatory, Naini Tal. The instrumentation used for taking observations has been described earlier (Goraya 1984). The Hilger and Watts monochromator with an exit slit admitting 50 Å of the spectrum to fall on the photomultiplier was used for taking spectrum scans. The star π Aqr was observed many times during a night and the continuum was drawn through each scan. Each scan was then reduced to instrumental magnitudes separately and all observations of individual stars during each night were averaged. The instrumental magnitudes were measured every 100 Å of the entire continuum. Along with π Aqr, the standard star ξ^2 Cet was also observed many times during a night for applying extinction corrections and to reduce instrumental magnitudes of π Aqr into absolute magnitudes. Our transformation of observations to absolute magnitudes of π Aqr corresponds to the absolute calibration system of Tug, White & Lockwood (1977). The standard deviation of the measurements on an individual night does not exceed ±0.03 mag in the entire wavelength range. Finally, the magnitudes were corrected for interstellar reddening and normalized to wavelength λ5500 Å. The reddening-corrected magnitudes thus obtained are listed in Table 1. A plot of these is shown in Fig. 1.

The infrared (*JHK*) observations of the star were obtained in 1980 October (Ashok *et al.* 1984) with the 104-cm reflector at the Uttar Pradesh State Observatory, Naini Tal, using a

Table 1. Dereddened normalized magnitudes of π Aqr normalized to wavelength λ5500 Å.

Wave-length (Å)	$1/\lambda(\mu^{-1})$	Magnitudes 1980 September 27	Magnitudes 1980 September 30	Wave-length (Å)	$1/\lambda(\mu^{-1})$	Magnitudes 1980 September 27	Magnitudes 1980 September 30
3500	2.86	−0.595	−0.600	5600	1.79	0.000	+0.005
3600	2.78	−0.570	−0.555	5700	1.75	−0.012	+0.025
3700	2.70	−0.531	−0.513	5800	1.72	−0.013	+0.040
3800	2.63	−0.499	−0.460	5900	1.69	+0.006	+0.026
3900	2.56	−0.596	−0.575	6000	1.67	+0.014	+0.031
4000	2.50	−0.560	−0.558	6100	1.64	−0.002	+0.014
4100	2.44	−0.543	−0.522	6200	1.61	−0.003	+0.030
4200	2.38	−0.475	−0.490	6300	1.59	+0.001	+0.050
4300	2.33	−0.443	−0.448	6400	1.56	+0.016	+0.047
4400	2.27	−0.387	−0.394	6500	1.53	+0.053	+0.098
4500	2.22	−0.360	−0.367	6600	1.51	+0.082	+0.080
4600	2.17	−0.320	−0.330	6700	1.49	+0.099	+0.108
4700	2.13	−0.279	−0.290	6800	1.47	+0.106	+0.160
4800	2.08	−0.234	−0.255	6900	1.45	+0.090	+0.158
4900	2.04	−0.195	−0.214	7000	1.43	+0.100	+0.150
5000	2.00	−0.120	−0.175	7100	1.41	+0.115	+0.185
5100	1.96	−0.131	−0.139	7200	1.39	+0.138	+0.180
5200	1.92	−0.100	−0.100	7300	1.37	+0.145	+0.212
5300	1.89	−0.065	−0.055	7400	1.35	+0.146	+0.204
5400	1.85	−0.033	−0.031	7500	1.33	+0.150	+0.225
5500	1.82	0.000	0.000				

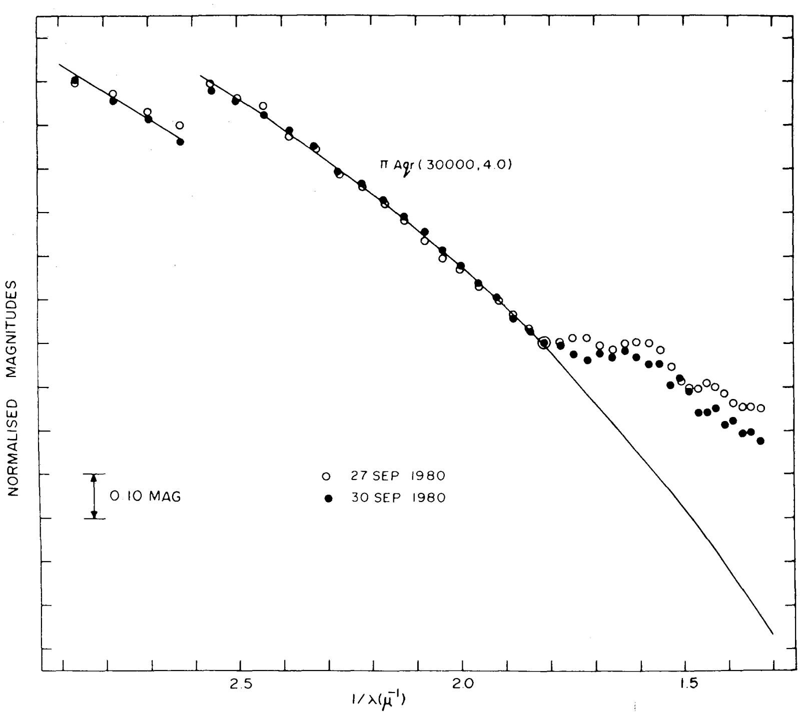

Figure 1. Dereddened normalized energy distribution of π Aqr (open and filled circles) compared to the computed model (continuous curve). The matching has been done by eye. The normalization has been done at $\lambda 5500$ Å which is indicated by a double circle. The normalized magnitudes are in terms of F_ν.

liquid-nitrogen-cooled InSb Photometer (Kulkarni *et al.* 1979) covering the J, H and K photometric bands. The star was again observed in 1983 December with the same IR photometer in the J, H and K photometric bands. The data were transformed to the Johnson JHK photometric system by using observations of standard stars (Johnson *et al.* 1966). The typical errors of observations are ± 0.07 mag in J, H and K magnitudes.

3 Corrections for interstellar reddening

The determination of interstellar reddening for Be stars is complicated due to their high rotational velocities and peculiar atmospheric structures. Rapid rotation introduces an intrinsic reddening which is significant for the rapidly rotating Be stars. Neglecting this effect yields an overestimate of interstellar reddening which in turn yields an over-correction of ultraviolet fluxes resulting in a spurious ultraviolet excess. Briot (1978) has found that an ultraviolet flux excess for B0e stars is related to an overestimate of interstellar reddening correction. This overestimate of reddening correction results in an ultraviolet flux excess observed for many Be stars.

The direct measurement of $E(B-V)$ neglects the effect of intrinsic reddening in Be stars. The normal Q method of Johnson & Morgan (1953), valid for the main sequence O and B stars, is likely to produce large errors because of an ultraviolet and near-IR excess emissions in a few of Be stars.

In order to account for intrinsic rotational reddening in π Aqr we have used the distance modulii method for the determination of colour excess, $E(B-V)$, of π Aqr. To determine interstellar reddening, we plotted colour excess, $E(B-V)$, (of about 60 normal B stars lying in the direction of the programme star) against their apparent distance moduli $(m_V - M_V)$. The $E(B-V)$ values for normal B stars were computed through the Q method. The normal B stars were selected from the *Photoelectric Catalogue* (Blanco *et al.* 1968). To estimate apparent distance modulii of normal B stars the M_V magnitudes were taken from the spectral type and luminosity class versus M_V calibration for early-type stars (Allen 1976). From the distance modulus versus $E(B-V)$ relation for normal B stars the $E(B-V)$ value of π Aqr corresponding to its distance modulus was estimated. The $E(B-V)$ value of π Aqr thus estimated is listed in Table 2 along with the expected error. The value of $E(B-V)$ determined by Beeckmans & Hubert-Delplace (1980) is also given in the same table for comparison. Their value of $E(B-V)$ agrees with ours closely. The reddening corrections were calculated by adopting a mean value of total-to-selective extinction; $R=3.25$ (Moffat & Schmidt-Kaler 1976) and using the interstellar reddening curve given by Lucke (1980) for the Aquarius region.

Table 2. Parameters of π Aqr.

Parameter	Value
Spectral type	B1Ve★
$\log g$	4.0
$T_{\rm eff}$	30 000 K
$E(B-V)$	0.08±0.02 0.07–0.12★
m_v	4.70±0.03

★Beeckmans & Hubert-Delplace (1980).

4 Continuum energy distribution

The continuum energy distributions in the optical region are very valuable for deriving the effective temperatures of early-type stars since most of their energy is emitted in this wavelength region. Because of the IR and ultraviolet excess emissions in Be stars some part of the Paschen continuum (longward of λ5500 Å) and Balmer discontinuity region is strongly affected. We have compared the $\lambda\lambda$4000–5500 Å region of the observed continuum energy distribution of π Aqr with the theoretical energy distribution computed by Kurucz (1979), for deriving the effective temperature. Fig. 1 gives the observed dereddened scanner energy distribution of π Aqr by open and filled circles. The Kurucz (1979) model (continuous line) with solar abundance and microturbulence velocity of 2 km s^{-1} has been superimposed on the observed spectra for deriving the effective temperature of π Aqr, assuming $\log g=4.0$ (Kontizas & Theodossiu 1980). The numbers in the brackets in Fig. 1 denote the values of $T_{\rm eff}$ and $\log g$ respectively of the best-fitting model. The uncertainty in the temperature derived due to photometric error of the observed fluxes is ±6 per cent. The fit of the theoretical models to the observed fluxes introduces an additional error that is around ±1000 K.

From Fig. 1 it is clear that the wavelength region $\lambda\lambda$3500–5500 Å of the observed continuum matches well with the model having $T_{\rm eff}$=30 000 K and $\log g$=4.0. The wavelength region longward of λ5500 Å deviates strongly from the model indicating strong near-IR excess emission. We also note from Fig. 1 that the near-IR excess emission is variable during the period of observation. The variation of IR excess emission is discussed in detail in Section 5.

Nordh & Olofsson (1977) have reported a temperature $T_{\rm eff}$=22 500 K and $\log g$=4.0 from their observed continuum energy distribution of π Aqr in 1972. However, our value of $T_{\rm eff}$=30 000 K is higher. The lower value of $T_{\rm eff}$=22 500 K found by Nordh & Olofsson (1977) is because of the strong IR excess emission of π Aqr in 1972 compared to our observations in 1980 October. As a result of strong IR excess emission, the $(B-V)$ colour index was more positive during 1972 thereby resulting in a less steep slope of the Paschen continuum and making the star redder and lowering the apparent effective temperature. From the temperature derived by us we can infer that the spectral type of π Aqr is B0Ve.

5 The IR excess emission

The IR excess emission is a common feature observed in the majority of Be stars. However the exact nature of IR excess emission is not clear due to limited amount of observational material in the IR region for a small number of Be stars. The most widely accepted explanation is that the free–free and bound–free emission originating in the ionized CS envelopes of Be stars give rise to the observed IR excesses (Gehrz, Hackwell & Jones 1974; Schild *et al.* 1974; Schild 1978; Scargle *et al.* 1978; Neto & Pacheco 1982). To study the exact nature of IR excess emission, simultaneous observations in the optical and IR regions are necessary. Such observations are presented in this paper.

In this present paper we have also combined our observations with all the previous available data from 1957–83 to understand the nature of IR excess emission observed in π Aqr. Because π Aqr shows strong IR excess emission and there also exists a large amount of observational data in the optical and IR region, this star is attractive for our purpose. The Johnson magnitudes were converted to log F_λ by using the absolute calibration given by Johnson (1966). Fig. 2 displays all the available data (in the form of log F_λ) on π Aqr in the visible and IR region (0.55–3.6 μm). It should be made clear that the data displayed in Fig. 2 include the broad-band standard

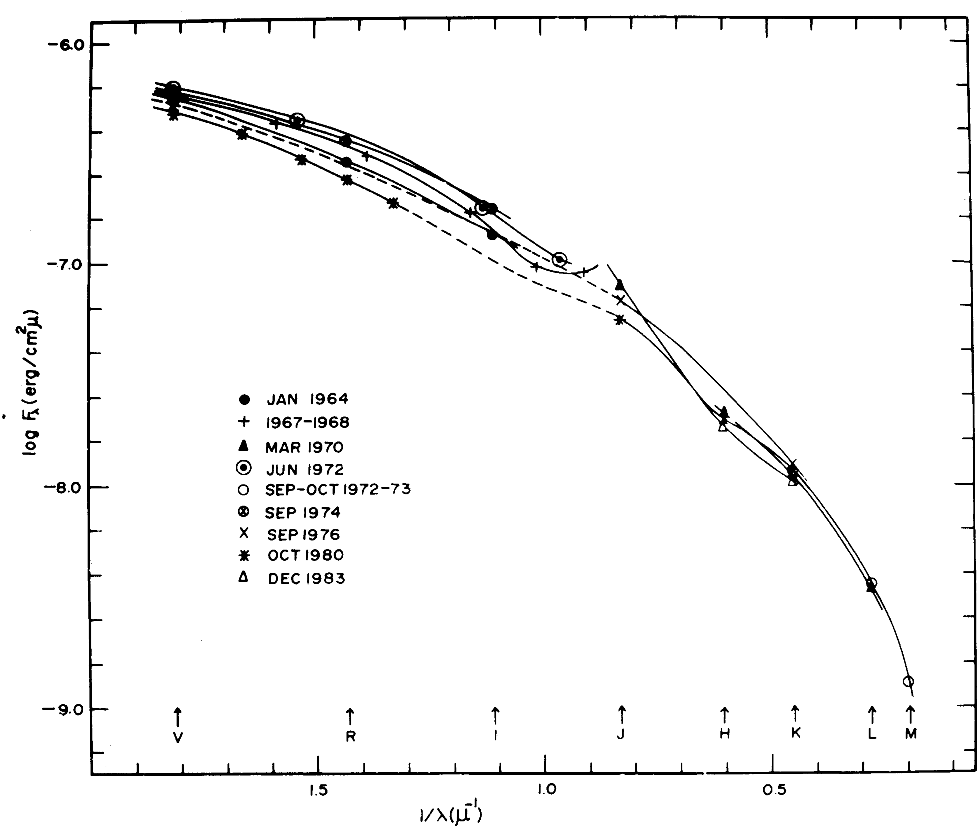

Figure 2. Variation of IR excess in π Aqr. The data have been collected from Johnson *et al.* (1966), Mitchell & Johnson (1969). Allen (1973), Nordh & Olofsson (1974), Gehrz *et al.* (1974), Fernie (1975), Jones (1979), Ashok *et al.* (1984) and the present paper. The observed points are connected by continuous curves. The dotted curves show the expected trend of the points observed simultaneously in the visible and IR region. The magnitudes are in the form of log F_λ.

magnitudes. The magnitudes in the *VRI* region also include 13 colour photometric measurements and scanner observations. Our scanner observations combined with the broad-band *JHK* magnitudes (Ashok *et al.* 1984) are also shown in Fig. 2. It is clear from Fig. 2 that our observations correspond to the minimum brightness of the star in *V* magnitude as compared to the previous available observations in the literature. Also we find that the IR excess emission was less strong than earlier. Fig. 2 reveals that the IR excess emission is variable in π Aqr. The variation is systematic and is accompanied by a variation in *V* magnitude. Obviously one can note from Fig. 2 that the brightening or fading in *V* magnitude is accompanied by strengthening or weakening of the IR excess emission respectively. The magnitude of variation of IR excess is more in *VRIJ* photometric bands than in *HKL* bands.

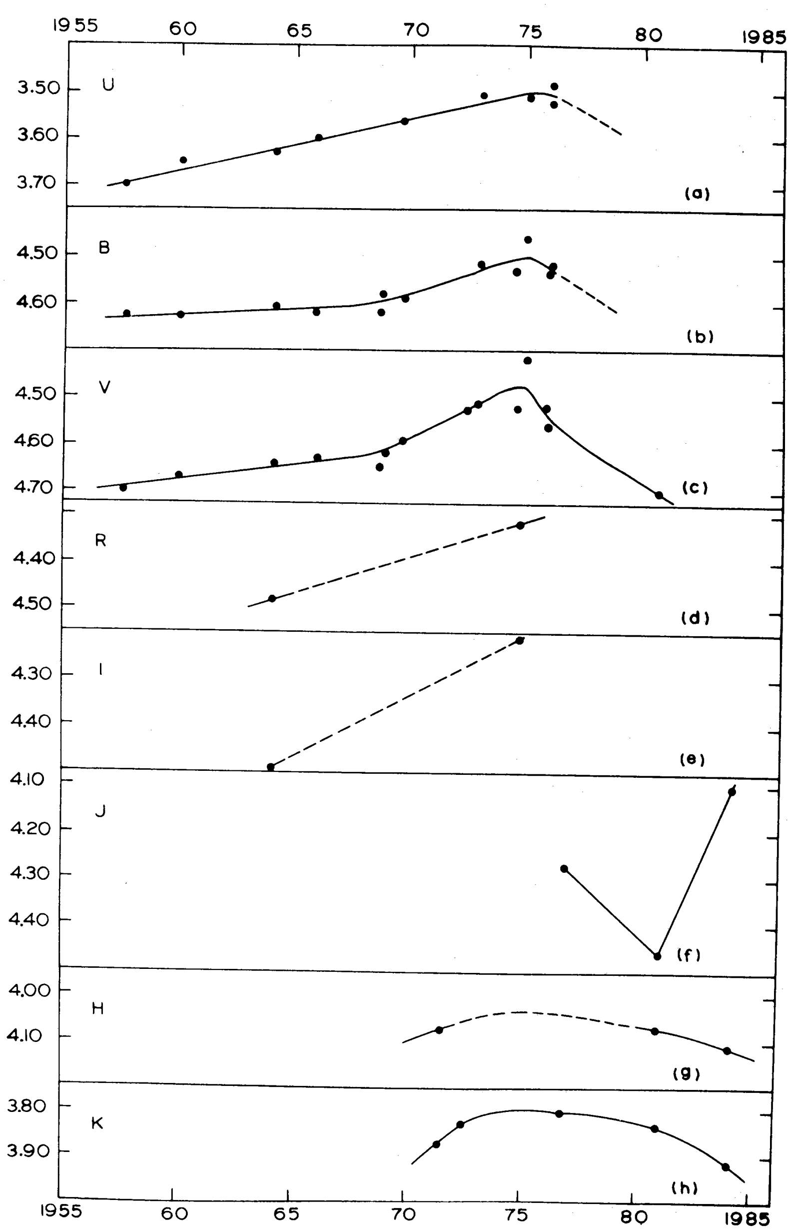

Figure 3. Long-term variation of π Aqr in different photometric bands. The data have been collected from Mendoza (1958), Cousins & Stoy (1962), Haggkvist & Oja (1966), Haupt & Schroll (1974), Nordh & Olofsson (1977) and the sources mentioned in Fig. 2.

The most interesting feature to be noted from Fig. 2 is that the IR excess has two separate emission peaks. The IR excess emission shows a dip between *I* and *J* bands. The first emission peak at $0.8\,\mu$m region has been interpreted as due to free–free and bound–free emission. The second emission peak which may fall somewhere in the $2–20\,\mu$m region is due to some unidentified source. More observations in the IR region extending to $20\,\mu$m are required to investigate the exact location of the second IR excess emission peak.

6 The variability in the *UBVRIJHKL* photometric bands

The detection of variability in *UBVRIJHKL* is a very useful diagnostic in the study of Be stars, as their energy distributions are becoming better understood. Variability in $(U-B)$ colour could indicate that the emission at the Balmer continuum had changed in amount. Variability in $(B-V)$ colour could indicate that the near-IR excess emission had changed in strength. And variability in $(V-R)$, $(R-I)$, $(I-J)$, $(J-H)$, $(H-K)$ and $(K-L)$ colours, etc. could tell us about the change in the strength of IR excess emission and the dynamics of the circumstellar envelopes of Be stars.

For the Be star π Aqr we have displayed in Fig. 3 all the available data in literature in the optical and IR region to investigate the nature of its variation. The data correspond to observations of this star obtained at different times, as indicated by the different symbols in Fig. 2. We have also included in Fig. 3 our simultaneous optical and IR observations obtained in 1980 October and 1983 December. Fig. 3 clearly reveals that π Aqr has brightened more or less monotonically in three filters (*UBV*) between 1957–74. The range of variation is 0.20 mag. The limited amount of data in *R*, *I*, *H* and *K* bands also show the increasing trend of brightness towards 1974. The flat portion of the light curves in Fig. 3 shows that the brightness of π Aqr was nearly constant during 1975. The decreasing trend of brightness between 1976 and 1981 is clear in the *V*, *J*, *H* and *K* photometric bands in Fig. 3. The same trend is indicated in the *U* and *B* filters also. The observations in *H* and *K* bands show the decrease in brightness during 1976 and 1984. Only one observation in the *J* band during 1983 December is opposite to this trend. For the present discussion if we omit this single measurement as not reliable, we can say that, in general, the brightness of π Aqr constantly decreased from 1976 to 1984. Therefore, Fig. 3 shows that the overall brightness of π Aqr in all photometric bands increased till 1974, remained constant during 1975, and then started to decrease till 1984. Thus it is obvious from Fig. 3 that π Aqr has a long-term light variation.

7 Discussion

The studies of continuum energy distribution by Schild *et al.* (1974) and Nordh & Olofsson (1977) show the ultraviolet excess emission and strong near-IR excess emission in π Aqr. However, our present observations indicate the absence of ultraviolet excess emission and show a weaker near-IR excess emission. Also our observations indicate a fainter *V* magnitude as compared to previous results. It is evident that the ultraviolet excess emission is related to the IR excess emission. The strong IR excess emission modifies the continuum of the underlying star, resulting in variable apparent effective temperature of π Aqr. It is clear from Fig. 2 that the IR excess emission in π Aqr increases with increasing brightness in *V* magnitude. Many studies (Divan, Doazan & Zorec 1982; Neto & Pacheco 1982; Dachs & Wamsteker 1982; Ashok *et al.* 1984) have shown that an increase in IR excess is also accompanied by an increase in Hα line emission and in luminosity in the visual in many Be stars including π Aqr. The polarization studies (Nordh & Olofsson 1977; Metz 1982) have shown that the degree of polarization is also well correlated with the brightness of π Aqr. In the present paper we have collected evidence to show that no significant short-term variations with time-scales of days, hours and minutes are present in π Aqr.

Significant long-term variation found in π Aqr is clear from Fig. 3. It is obvious from Fig. 2 that the increase or decrease in brightness in V is well correlated with ultraviolet excess emission and IR excess emission. Thus it is concluded that π Aqr exhibits simultaneously, with an increase or decrease in V brightness, an increase or decrease in the near-ultraviolet excess emission, the IR brightness, and the equivalent width of Balmer line emission. From this type of variation we infer that π Aqr has variation of type I (Dachs 1982). The variation of type I indicates that in this case broad-band magnitude variations are caused by variable amounts of continuous hydrogen recombination radiation emitted from a circumstellar envelope of variable density and dimension. Analysis of the slope for the correlation between photometric and Balmer line variation of type I shows that Be star envelopes are optically thick for Hα line radiation (Dachs 1982).

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