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ASTRONOMY AND ASTROPHYSICS

Study of nova shells

II. FH Serentis 1970 and QU Vulpeculae 1984, nebular expansion, parallax and luminosity*

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Abstract. We present Hα direct imaging and shell spectroscopic observations of two classical novae: FH Ser 1970 and QU Vul 1984. The distances, reddenings, luminosities at maximum, and the mass of the shell ejected by FH Ser are derived and discussed.

Key words: galaxies: individual: NGC 1380 – novae: cataclysmic variables – stars: distances

1. Introduction

Spatially resolved images of old novae in narrow filters, coupled with spectroscopic measurements of the expansion velocities of the ejecta, provide the observational grounds to measure the distance to novae via nebular parallaxes (e.g. Cohen and Rosenthal 1983). In this respect we note that the observations obtained with the new generation of 4m-class telescopes under sub-arcsec seeing conditions, or better yet with *HST*, have dramatically increased the number of objects for which it is possible to study the structure of the surrounding nebula and the geometry of the explosion (e.g. Shara et al. 1996, Slavin et al. 1995), whereas in the past such an analysis was reserved only to an handful of objects (e.g. Hutchings 1972).

In this paper we present new observations carried out at Asiago and La Silla Observatories on two classical novae: FH Ser 1970 and QU Vul 1984. The direct determination of the distance of these objects is of particular interest.

FH Ser belongs to the class of novae like DQ Her 1934, which form dust in the envelopes during the 'transition' phase. The lightcurves of these novae are characterized by a sudden change of the slope, at about 2-3 magnitude below maximum, which leads the nova towards a very deep minimum and normally lasts a few weeks (followed by a secondary maximum). In these cases, the use of the Maximum Magnitude vs. Rate of Decline Relationship (=MMRD hereafter) to determine the distance to the nova could be severely hampered by the presence of such a dip just in the range of magnitudes where the rate of decline is normally measured. Thus, the measure of parameters t_2 and t_3 for this class of novae is normally rather uncertain. Another motivation for the study of the nebula surrounding FH Ser stems from the fact that the quality of the data presented in this paper allow us to measure the mass of the nebula ejected by the nova. We note that the mass of the ejecta is known only for a dozen of classical novae (see Warner 1995) although this quantity is considered a key-parameter for nova theories (e.g. Livio 1994).

The case of QU Vul 1984 is quite different, but no less interesting. QU Vul is likely to be one of a few novae arising from an O–Ne–Mg white dwarf (Livio and Truran 1994). Recently, Starrfield et al. (1992) have raised the interesting possibility that O-Ne-Mg could not follow the MMRD relationship which normally holds for novae coming from C–O white dwarf. This hint could find some kind of observational support in Nova LMC 1990 n. 1. This peculiar object, indeed, shows a significant neon enrichment (Dopita et al. 1992) in such a way that one is allowed to include it among the O–Ne–Mg novae, moreover it deviates from the MMRD relationship by more than 1 magnitude (Della Valle 1991). It is apparent that a direct determination of the distance to QU Vul could probably help clarify whether or not O–Ne–Mg novae follow the MMRD relationship (see also Della Valle and Livio 1995).

Finally, we point out that Taylor et al. (1987) have determined the distance to this nova by measuring the nebular parallax through the radio image. It will be of particular interest to compare distances obtained with the same methodology applied at different ranges of wavelengths.

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* Based on data collected at the European Southern Observatory, Chile

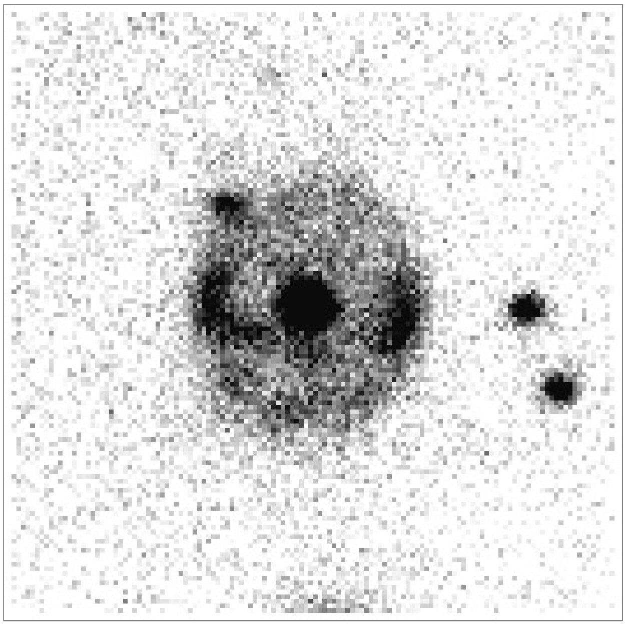

Fig. 1. The Nebula surrounding FH Ser 1970. The East is at the top, North is right

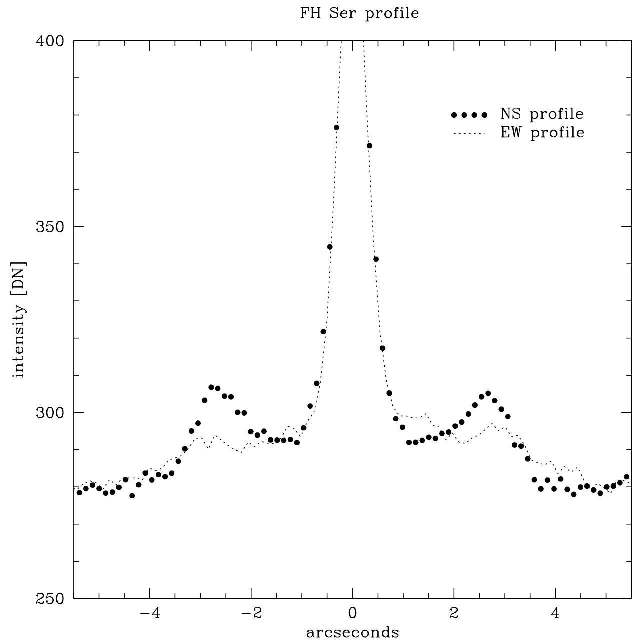

Fig. 2. Cross sections pf Fig. 1 along E–W and N–S directions

2. Nova FH Ser

Nova FH Ser was discovered by Honda (1970) on 1970 Feb 13 during the rise to maximum. At peak light the nova reached V = 4.4 (Borra and Andersen 1970). Around maximum the spectrum of the nova mainly exhibited strong emission lines of H, Fe II and Ti II and low expansion velocities: from 500 to 1000 km/s (Rosino, Ciatti & Della Valle 1986, hereafter RCD86). These features are quite typical of the spectroscopic class of 'Iron' novae introduced by Williams (1992). After a rather slow first decline ($t_2 \sim 35^d$), the nova suddenly decreased its brightness by more than 4 magnitudes in about 45 days as a consequence of the absorption due to the dust formed inside the ejecta. Immediately after this minimum, the nova newly increased in brightness and, after reaching a second maximum, a few weeks later started to monotonically decline towards the pre–nova brightness.

2.1. The nebula

The image of FH Ser shown in Fig. 1 is the stacked frame of two 10m exposures. They were obtained on March 17 1996 with NTT+SUSI in Hα + N[II] filter under very good seeing conditions ($\sim 0''.55$), and good spatial sampling ($0''.13$/pixel). Fig. 1 shows the nova embedded in a faint elliptical nebulosity and surrounded by a well defined 'equatorial ring' having an apparent inclination of $\sim 60°$ (90° corresponding to the edge on view of the ring) in agreement with the Duerbeck's (1992) measurement of $\sim 58°$.

To measure the size of the nebula we have plotted in Fig. 2 cross sections through the central star and the nebula along the E–W and the N–S directions. The N–S cross section intersects the two bright blobs of Fig. 1 and represents the apparent minor axis of the nebula. A 3 gaussian fit of its intensity profile yields an outer diameter of the shell of $7''.6$, while the 'peak to peak' diameter results of $5''.4$. The intensity profile of the E–W cross section gives an outer diameter of about $9''$.

From the 'peak to peak' diameter we derive an angular expansion rate of $0''.104$ per year whereas the 'outer diameter' gives $0''.146$/yr. The values measured by Seitter and Duerbeck (1987) and Duerbeck (1992) of $0''.128$ and $0''.136$, in 1984.6 and 1989.6, would indicate that they have measured the radius of the nebula at an intermediate value between the 'outer' and the 'peak to peak' measurements reported above.

2.2. The expansion velocity of the expanding shell

Although the analysis of the geometry of the shell ejected by the nova was not within the main purpose of this paper, nevertheless a 'first order' modeling of the shell is necessary to derive from the spectroscopic measurements the 'true' expansion velocity, v_{exp}, which has to be introduced into [2] to determine the distance d to the nova

$$d = 0.207 \times (v_{exp} / \dot{\theta}) \qquad [2]$$

With this in mind, we show in Fig. 3 a spectrum of FH Ser obtained at La Silla on March 13, 1994 with the 3.6m telescope + EFOSC. The $1''.5$ slit, corresponding to a resolution of about 8 Å , was oriented along the E–W direction. The structure of the Hα emission appears surrounded by the two fainter emissions due to the [NII] doublet at 6548, 6564 Å , and is typical of an expanding shell whose velocity field departs from the spherical symmetry (see also the case of DQ Her 1934, Herbig and Smak 1992). This fact, coupled with the elliptical shape of the nebula and the presence of the 'equatorial belt' lying on a plane inclined by about 30° with respect the line of sight, would suggest that the

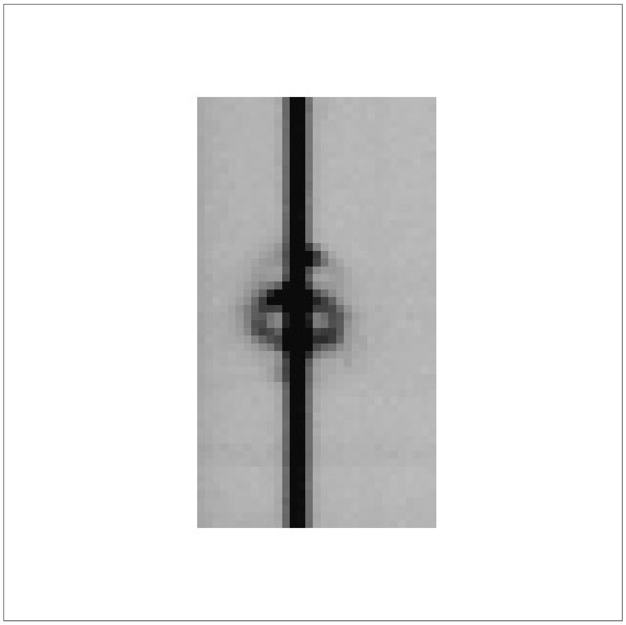

Fig. 3. Enlargment of the spectrum of FH Ser around the Hα+[NII] region

shell can be approximated to an expanding prolate ellipsoidal with its major axis forming a 60° angle with the line of sight.

The tilting of the major axis of the nebula of Fig. 1 indicates that the ellipsoidal is also sloped by $\sim 15° - 20°$ with respect to the E–W direction. The monodimensional trace of the spectrum of Fig. 3, presented in Fig. 4 (note that the spectrum has been already corrected for the interstellar absorption, see below), shows a faint, relatively blue, continuum with superimposed emission lines of the Balmer series, HeII, NIII and [OIII]. The Hα + [NII] emission structure has been approximated by a simultaneous multiple gaussian fit assuming the border condition that the 6548 Å component of [NII] is about 1/3 of the 6583 Å one. The result are double peaked profiles for all the emissions with peak to peak velocities of 384 ± 15 km/s, for Hα, and 410 ± 22 and 360 ± 20 km/s for the two [NII] satellites. These figures are consistent with the expansion velocity measured from the Hβ line, which also exhibits a saddle-shape profile, filled in by a fainter emission and showing a peak to peak velocity of 380 km/s. These measurements of radial velocities agree, within 10%, with the mean radial velocities derived by RCD86 on spectra obtained during the late nebular stage of the nova in the period 1975 and 1978. By assuming a projected (along the line of sight) radial velocity of 380 km/s, an expansion rate of $0''.104$ per yr and an inclination of 60°, we find a distance to the nova of 870 pc, the attached error being $\lesssim 10\%$.

An alternative estimate of the expansion velocities comes from the FWHM of the Balmer lines, which, in our case, would correspond to about 500 km/s. This larger value is easily explained if one assumes that the outer and faintest regions of the nebula are moving faster than the internal ones. In this case, using the size of the minor axis of the nebula ($7''.6$) and 26 yrs as the time since the nova explosion, the angular expansion rate

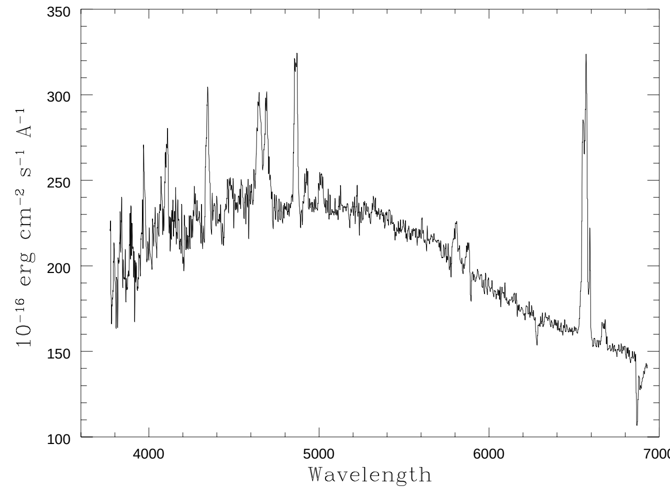

Fig. 4. The optical spectrum of FH Ser obtained with the 3.6m+EFOSC at La Silla

to be introduced in [1] is $0''.146$ per year. From these figures we derive a distance to the nova of 840 pc.

2.3. The $H\alpha$ emission from the central object

From the frame of the spectrum shown in Fig. 3 it is possible to derive the approximate profile of the Hα emission emitted by the the nova remnant, namely the accretion disc. To this aim, we have tentatively subtracted from the spectrum of the star the spectrum of the nebula averaged over the two scan lines which are immediately adiacent to the stellar continuum. The result is a single-peaked profile with a FWHM of about 840 km s^{-1}. If the observed emission line is produced by the accretion disk of the nova binary system, then 420 km s^{-1} might represent an estimate of the rotational velocity of its outer edge. This seems to be a reasonable value for the accretion disc of a close binary and it does not require a large correction for projection effects due to the small inclination of the orbital plane to the line of sight. In fact, in the hypothesis that the equatorial belt of Fig. 1 lies in the same plane as the accretion disk, the inclination of the nova binary system would be of about 60°. It might be worthy to note that this inclination also represents a limit for the detection of eclipses.

2.4. The reddening and the absolute magnitude at maximum

The interstellar extinction toward the nova is likely to be an 'estimated' quantity rather than a 'measured' one in view of the many uncertainties which are involved in its measurement. Following Della Valle and Duerbeck (1993), we shall use the following approaches to derive the reddening to the nova: **a**) the color of the nova at maximum; **b**) the Balmer decrement; and **c**) the EW of the Na I λ5890 interstellar absorption.

a) According to the compilation of van den Bergh and Younger (1987) the average color of a nova at maximum light is $(B-V)$ = +0.23, whereas the color of FH Ser is $(B-V)_{max}$ = 1.05 (RCD86). Therefore we find $E(B-V)$ = 0.82.

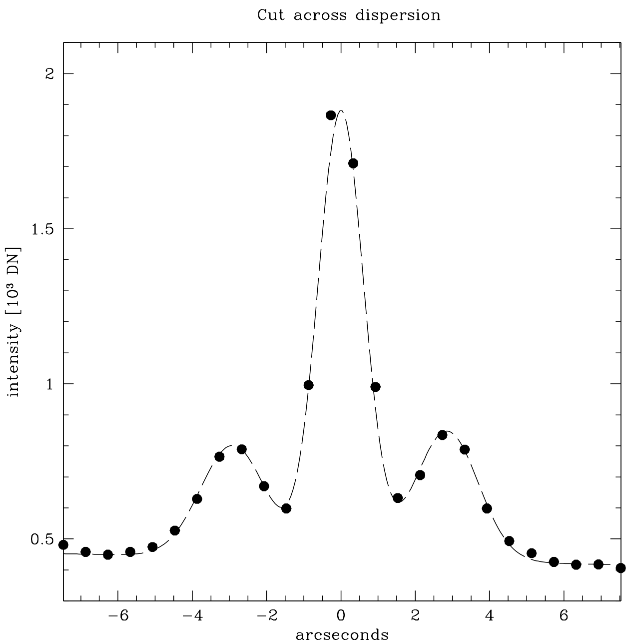

Fig. 5. The cross section of the image reported in Fig. 3 along the dispersion

b) Assuming a theoretical ratio $H\alpha/H\beta \approx 2.9$ (case B), we measure from the spectrum of Fig. 3 a ratio flux($H\alpha$/[NII]) of ~ 2.5 and $H\alpha/H\beta \approx 5.7$, the latter value being slightly smaller than the value measured by RCD86 on a spectrum obtained in Aug 1978. Indeed, as shown by Whitney and Clayton (1989) steep values of the Balmer decrement may not be attributed only to the reddening, but also to optical depth effects which make the $H\alpha$ particularly strong. However, at very late stages of the nova evolution, the observed ratios seem to converge. From the Balmer decrement we derive an $E(B-V) = 0.61$.

c) The EW of the interstellar absorption line of Na I λ5890 correlates, according to Barbon et al. 1990, as EW(NaI)$\sim 0.25\times E(B-V)$. An inspection of the spectrum of Fig. 4 shows that the Na D absorption is superimposed on the broad HeI emission lines at 5876. By applying a double simultaneous gaussian fit, we derive EW=2 Å which in turn yields E(B–V)=0.5.

The average of the three methods gives E(B–V)=0.64 $\pm$ 0.16 in agreement, within the errors, with the value obtained by Duerbeck (1992). FH Ser reached at maximum a magnitude of V=4.4; by assuming the distance and the reddening reported above, and a typical ratio A_v/E(B-V)=3.2 (Seaton 1979), we derive an absolute magnitude at maximum of $M_V = -7.2\pm0.3$ (see also Duerbeck 1992).

If we introduce the rate of decline of 0.057 mag per day (RCD86) into the MMRD, recently re-calibrated by Della Valle and Livio (1995), we derive $M_V = -7.3$. The agreement between these figures, derived through the use of two independent approaches, lends a piece of empirical support to the assumptions which have been introduced in the previous paragraphs.

2.5. The mass of the ejected shell

We are now in the position to give an estimate of the mass of the expanding shell under relatively simple assumptions. From the spectrum of Fig. 4, we derive a flux in the $H\alpha$+[NII] lines of $F_{H\alpha} = 5500\times10^{-16}$ erg s^{-1}, where $\sim 60-70\%$ of the light is emitted by $H\alpha$.

First, we must consider that the area of the sky covered by the slit is 34% that it is covered by the nebula. However, since the slit is oriented E–W and does not include the contribution of the bright blobs, it gathers only $\sim$ 29% of the total flux.

Secondly, we need to account for the contribution to the emission lines by the central star. Aperture photometry of the central star performed on the $H\alpha$–on frame yields a flux ratio $\mathrm{Flux}_{nebula}/\mathrm{Flux}_{star} \sim 3$. By combining all the previous figures we find that the actual H_α flux emitted by the whole nebula is 5.2×10^{-13} erg cm^{-2} s^{-1}. The $H\alpha$ emission from the envelope is $E_\alpha = g_\alpha \times n_e^2 \times Volume$ erg s^{-1}, where g_α is the emission coefficient per cm^3 and for $n_e = 1$. This quantity is a function of the temperature and, for T=10000 K, is $g_\alpha = 4\times10^{-25}$ erg cm^3 s^{-1} (Boyarchuck et al. 1968). On the other hand, the spectrum would indicate that the temperature is likely to be smaller than 10000° K, probably intermediate between 5000° and 10000° K (see also Hartwick and Hutchings 1978). In this case, we use a value for the emission coefficient per cm^3 which is a factor $\sim$ 1.5 larger than quoted before. By assuming that the volume of the expanding shell is V$\sim 4\pi\times R^2\times\delta$, where $\delta = fR$ (with f smaller than 1) is the thickness of the shell, one obtains:

$$n_e^2 = \frac{F_{H\alpha}}{f\,d\,\theta^3\,g_\alpha} \qquad [2]$$

If the volume of the shell is not uniformly filled in because the material condensated in blobs (e.g. GK Per 1901), one has to introduce in [2] the filling factor b. Following Mustel and Boyarchuck (1970), an estimate of the thickness of the envelope can be derived by assuming that the shell grows in thickness because of thermal motions inside the gas, therefore, for T=7500° K, $\delta \sim v_{ther}/v_{exp} \lesssim 0.1$. Finally, for $b = 1$, d=870 pc and $\theta = 5''.4/2 = 2''.7$, we obtain $n_e \sim 10^3$ and $M_{env} = 4.7\times10^{-5}$ $M_\odot$. This is in good agreement with the estimate of 4.5×10^{-5} $M_\odot$ derived by radio observations (Hjellming 1990). However, we note that this result should be likely regarded as a lower limit. First of all, the thickness of the nebula could have been underestimated. The profile of Fig. 3 across the direction perpendicular to the dispersion (see Fig. 5), after the deconvolution for the seeing, suggests a thickness corresponding to $f = 0.55$. We note that Humason (1940) derived for the shell surrounding DQ Her, $f = 0.5$. Moreover, the filling factor, b, might be smaller than one. Looking at Fig. 1 the nebula does not appear homogeneously filled in, therefore $b \sim 0.5$ could be a more likely guess. After applying these correction factors the mass of the envelope turns out to be $\sim 2\times10^{-4}$ $M_\odot$.

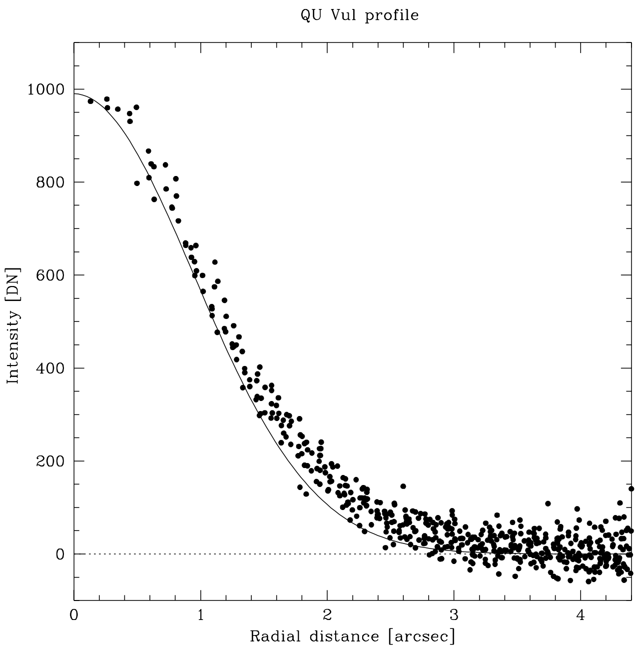

Fig. 6. The PSF of QU Vul (black dots) compared with the average PSF of 11 nearby field stars (solid line)

Table 1.

Line	λ	Flux
[NeIII]	3869.3	1269
H8	3890.9	338
[NeIII]	3968.2	611
[SII]	4073.1	431
Hδ	4099.8	871
Hγ	4338.5	1042
HeI	4465.0	836
NIII	4641.4	573
HeII	4684.4	1315
[NeIV]	4719.0	164
Hβ	4862.1	2072
[OIII]	4958.1	220
[OIII]	5006.0	936
HeII	5409.5	153
[FeIV]	5677.4	137
HeI	5874.6	730
Hα	6561.1	6842
HeI	6676.8	223
HeI	7063.5	84
[OII]	7324.0	305
HeII	8235.7	280

3. Nova QU Vul 1984

Nova QU Vul 1984 has been extensively studied in the optical range from maximum light through the late decline by Rosino et al. (1992) and Saizar et al. (1992). The nova attained its maximum on December 25 at V=5.5 and B=6.25 and a t_2 of 22 days was derived from the lightcurve during the first decline of the nova. This object was newly observed at Asiago on July 9 and 10 1994, using the 1.8m telescope and the CCD camera. Two Hα images with exposure times of 1h and 45m and a 15m frame in the nearby continuum were obtained. From the analysis of these images we have measured the FWHM of the nova to be $2''.45 \pm 0.05$, whereas the average FWHM of 11 nearby field stars gives $2''.26 \pm 0.03$. No difference (within $\lesssim 0''.05$) between the nova and the field stars is observed in the continuum light. These results allow us to conclude that we have resolved the nebula surrounding the ex–nova, at a confidence level of $\sim 3\sigma$. Fig. 6 shows a radial profile of the nova (black dots) in comparison with the average PSF profile (solid line) obtained by the field stars.

The spectrum presented in Fig. 7 is the average of two exposures, 1h each, obtained on 10 and 11 August 10 1994 at La Silla with the 1.5m telescope + BC spectrograph with a resolution of about 7 Å . The spectrum has been corrected for an interstellar extinction of A_V = 1.7 mag (in good agreement with the value of 1.9 estimated by Saizar et al. 1992), which has been obtained from the comparison of the $(B–V)_{max}$ of QU Vul with the average color of novae at maximum and from an observed Balmer ratio of Hα/Hβ=5.5. In Tab. 1 we report the identified lines (col. 1) the measured central wavelength (col. 2) and the flux (col. 3) in units of 10^{-16} erg cm^{-2} s^{-1}.

The spectrum exhibits emission lines with moderate degree of ionization and rectangular flat–topped or saddle–shaped profiles. The quality of the images on the Hα frames does not allow us to disentangle significant deviations of the expanding shell from the spherical symmetry, therefore we can only derive a first order approximation for the size of the nebula. By deconvolving the profile of the nova (black dots in Fig. 6) with the PSF (solid line in Fig. 6), we derive a radius of $r \sim 0''.95$, which in turn gives an expansion rate of $0''.095$ per year. The linear expansion velocity that has to be associated to this angular expansion rate also cannot be properly evaluated because of the lack of any information on the geometry of the expanding shell. Tentatively, we measure from the FWZI of Hα+[NII], Hβ, and Hγ an expansion velocity of 1260, 1240, 1070 km s^{-1} respectively. By assuming an average value of 1190$\pm$105 km s^{-1}, we derive a distance of 2600$\pm$200 pc, which is a 30% smaller than it has been derived by Taylor et al. (1987). However, we have to point out that this result should be taken with some degree of caution in view of the many uncertainties that are involved.

4. Conclusions

In this paper we have presented and discussed new observations for two 'recent' old–novae: FH Ser 1970 and QU Vul 1984.

Sub-arsecond imaging of FH Ser obtained with NTT+SUSI in Hα+[N II] filter, under good seeing conditions, shows the old nova embedded into an elliptical nebula with semi-axes $a = 4''.5$ and $b = 3''.8$. These observations coupled with the spectroscopic analysis of a spectrum obtained at the 3.6m telescope+EFOSC, would suggest that FH Ser is surrounded by an expanding prolate shell with major axes forming an angle of $\sim 60°$ with the line of sight. We have obtained a distance to the nova of 870 pc, which

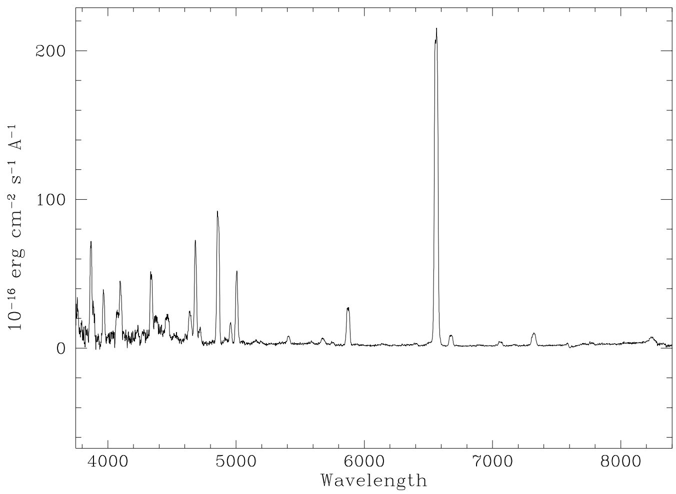

Fig. 7. Average of two optical spectra of QU Vul obtained with the 1.5m telescope+BC spectrograph al La Silla on 10 and 11 August 1994

is in agreement, within the errors, with the values obtained by Duerbeck (1992) and Slavin et al. (1995). This distance also implies an absolute magnitude at maximum of $M_V = -7.2 \pm 0.3$ in good agreement with the absolute magnitude provided by the MMRD. After applying the bolometric correction of –0.1, suggested by Duerbeck (1992) for a value of the reddening similar to that used in this paper, we obtain $M_{bol,max} = -7.3$, which is still in agreement (within the errors) with the value of the Eddington limit of $M_{bol,max} = -7$, for slow novae at maximum (Starrfield 1988).

Finally, from the intensity of Hα we have measured the mass of the shell, which turns out to be larger than $\sim 5 \times 10^{-5}$ $M_{\odot}$, likely of the order of $\gtrsim 2 \times 10^{-4}$ $M_{\odot}$.

The case of QU Vul 1984 has been discussed on data obtained at both the Asiago Observatory with the 1.8m telescope and La Silla with the 1.5m telescope + B&C. The quality of the material does not allow us to set 'robust' conclusions. Analysis of two Hα+ [NII] frames finds that the PSF of the nova is ~ 10 % larger (significance $\sim 3\sigma$) than average PSF of nearby field stars. This result implies an average expansion rate of $0''.095$ per year and a distance to the nova of 2600$\pm$ 200 (1σ internal error) pc. This result is marginally consistent, within the errors, with the distance obtained by Taylor et al. (1987) via radio–parallax measurements. Once one has assumed an E(B–V)=0.5 (Rosino et al. 1992), the absolute magnitude at maximum of QU Vul turns out to be $M_V = -8.2(\pm 0.5)$. The central value is about 0.4 magnitude brighter than expected from its rate of decline, but still within the scatter ($\sim 2\sigma$) of the MMRD relationship.

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