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Spectral study of V565 Mon: probable FU Ori-like or chemically peculiar star

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Abstract We present a detailed spectroscopic study of pre-main sequence star V565 Mon, which is the illuminating star of the Parsamian 17 cometary nebula. Observations were performed with the 2.6 m telescope in Byurakan Astrophysical Observatory on 2018 February 15. Radial velocities and equivalent widths of the most prominent lines of V565 Mon are presented. We build the spectral energy distribution and estimate the main parameters of the star, for example the obtained bolometric luminosity of V565 Mon is $L_{V565} \approx 130\,L_{\odot}$. Considering all features of V565 Mon, we come to the conclusion that this young intermediate-mass star belongs to some intermediate class between T Tau and HAeBe stars. Very unusual for a young star is the presence of strong absorption Ba II lines in the spectrum. Possible explanations on this issue are discussed. Hence, we think that V565 Mon is a unique example, which can help to understand some open questions involved in the problem of nucleosynthesis in young stars.

Key words: stars: pre-main sequence — stars: variables: T Tauri — Herbig Ae/Be stars: individual: V565 Mon

1 INTRODUCTION

V565 Mon belongs to a little studied star formation region. As a variable star, it was discovered by Hoffmeister (1968). It is the illuminating star of the Parsamian 17 reflection cometary nebula, in which it is deeply embedded (Parsamian 1965; Cohen 1974). The observational data about this star are scarce. A first description of the morphology of the nebula and the multi-band infrared (IR) observations of the central star, which revealed that V565 Mon is a prominent IR source, were given in the work of Cohen (1974). Only after 10 years was this object reobserved photometrically by Neckel & Staude (1984). The spectrum of the star was briefly described in the Herbig & Bell (1988) catalog, where V565 Mon is listed as HBC 546. The spectral type was very roughly estimated as G, with Hα emission line and very strong BaII lines in the red part. A next important step in the study of this star was the identification of V565 Mon with the IRAS 06556-0752 source in the catalog of Weintraub (1990). This confirmed that V565 Mon is extremely bright in the mid-IR range.

The P17 cometary nebula, also known as NGC 2313, PP67 and GN 06.55.6.01 (Magakian 2003), is an object with high surface brightness in the dark cloud LDN 1653, the distance of which is 1060 $\sim$ 1200 kpc (Kim et al. 2004; Maddalena et al. 1986; Hilton & Lahulla 1995). P17 has a triangular shape and V565 Mon is located in its south-western edge. On deep images with a high spatial resolution, one can note traces of the second, opposite cone, which suggests a bipolar structure of the nebula. In the course of the search for Herbig-Haro (HH) objects, a group consisting of HH 947 A/B was discovered (Magakian et al. 2008) near the symmetry axis of P17. Logically, V565 Mon can be considered as a source of this flow.

In the image taken from the Pan-STARRS survey, one can see V565 Mon immersed in dust. The aforementioned HH group is also visible and pointed out by arrows in the left corner of Figure 1. For comparison in Figure 2, we present the same field taken from the AllWISE survey colored chart.

All of the above makes the V565 Mon star an interesting target for further studies. Especially noteworthy is that we still do not have good spectral data on this star. Thus, it was included in our program of spectral studies of selected pre-main sequence (PMS) stars.

2 OBSERVATIONS AND DATA REDUCTION

Observations were carried out with the 2.6-m telescope of Byurakan Astrophysical Observatory on 2018 February 15. We utilized the SCORPIO spectral camera

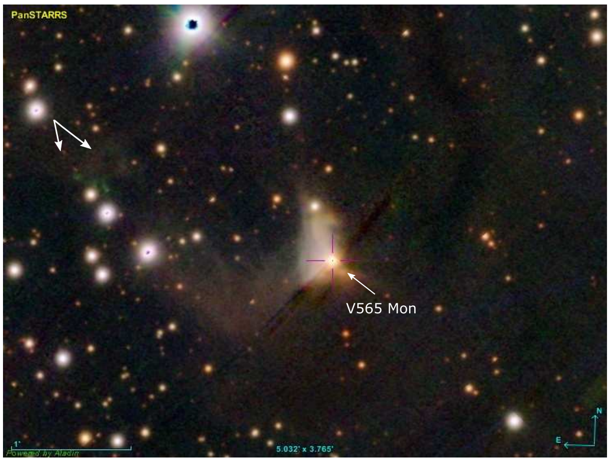

Fig. 1 Color image of a field around V565 Mon from Pan-STARRS Data Release 1 (DR1) survey (i, r, g filters). HH objects are pointed out by arrows in the left corner. The dark diagonal stripe, visible across the nebula, is an artifact.

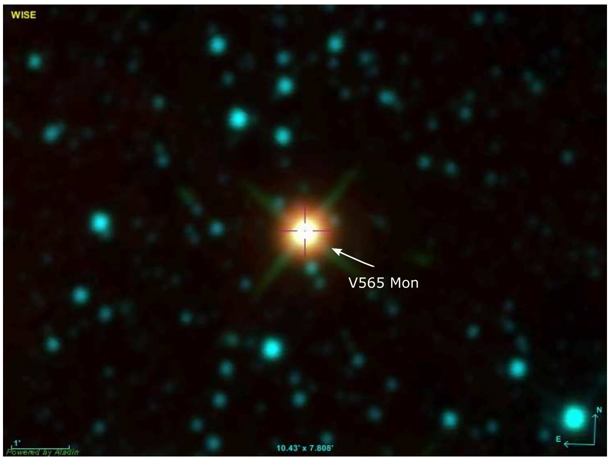

Fig. 2 The same field from the AllWISE survey (blue - 3.4 µm, green - 4.6 µm, red - 22 µm). V565 Mon is pointed out by a white arrow.

(Afanasiev & Moiseev 2005) at the prime focus of the telescope. The e2v CCD42-40 2080×2048 CCD was used as a detector, which works in imagery and long-slit modes. In long-slit mode, the width of the slit was $1.5''$ (with seeing about $2.5''$) and the length was about $5'$. As a dispersive element, the volume phase holographic grating with 1800 g mm^{-1} was employed, providing the spectral resolution of about $R = 2500$. For the wavelength calibration, the Ne+Ar lamp was referenced as a comparison spectrum. Total exposure was 3600 s, which provides signal to noise ratio (S/N) more than 100 in the final spectrum after the processing and optimal extraction. Data reduction was done in the usual way, applying the ESO-MIDAS program and appropriate packages. The stellar spectrum was extracted in a $2''$ width zone, while background and night-sky emission lines were modeled along the all slit length. Our observations cover the wavelength range of approximately 5800–6900 Å.

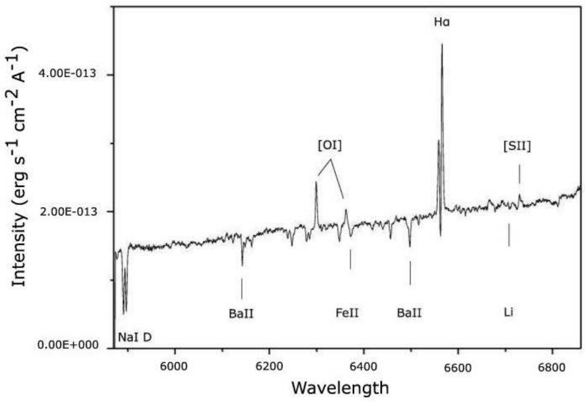

Fig. 3 Spectrum of V565 Mon in absolute intensities.

3 RESULTS

3.1 General Description of the V565 Mon Spectrum

During our observations, the visible brightness of V565 Mon was similar to the previously reported values. The reduced spectrum is presented in Figure 3. One can see a red continuum with both emission and absorption lines superposed. Strong Hα emission is divided by a relatively narrow (in comparison with the emission) absorption component, which is going below the continuum. Such a double-peaked profile of the Hα line is typical for young active stars, although such strong central absorption is rare.

Among the most prominent absorption lines is a strong but quite narrow NaI D doublet. Besides, two $\lambda 6141.71$ and $\lambda 6496.89$ BaII absorption lines are very noticeable, which were already mentioned in the Herbig & Bell (1988) catalog. We also noticed a weak 6707 LiI resonance line, which is a well-known youth indicator for PMS stars (Herbig 1964; Takeda & Kawanomoto 2005; Lyubimkov 2016). Also, a variety of FeII absorption lines exist, but no FeI absorptions were detected. Besides Hα, the only other emission lines detected are forbidden red doublets of [OI] and [SII]. Taking into account the presence of HH flow, associated with this star, one can assume that they belong to an outflowing envelope or jet near the star. A more or less accurate spectral type of V565 Mon still is difficult to estimate. In any case, the prominent NaI D lines, on the one hand, and well-developed FeII spectrum with absence of FeI lines, on the other hand, lead to a spectral range from late F to early G, confirming Herbig's assumption.

3.2 Equivalent Widths and Radial Velocities

We estimated the equivalent widths (EWs) and heliocentric radial velocities of the most prominent absorption and emission lines and present them in Table 1. In case of Hα, we list separate measurements for emission and absorption components.

One can see that negative radial velocities are observed only for forbidden lines, which confirms our assumption that these lines are related to HH outflow. Moreover, low absolute values of their velocities point to a large angle of outflow with respect to the line of sight. The absorption component of Hα has near-zero velocity, and all other absorption lines, including NaI D, have positive velocities. In general, the strength of emission lines is not high. Even for Hα emission, the total EW is ≈ -7 Å.

Table 1 EWs and Heliocentric Radial Velocities of Selected Lines in V565 Mon Spectrum

Lines	EW (Å)	V_R (km s^{-1})	FWHM
Na I D$_2$ (5889.96)	2.10	36	1.94
Na I D$_1$ (5895.93)	1.88	32	3.84
Ba II (6141.71)	0.83	62	2.62
[O I] (6300.31)	−1.67	−36	3.88
[O I] (6363.82)	−0.58	−51	4.65
Fe II (6456.39)	0.45	24	3.92
Ba II (6496.89)	1.06	32	3.09
Fe II (6516.05)	0.2	17	3.02
Hα (em)	−2.22	−181	3.61
Hα (abs)	0.22	−2	3.92
Hα (em)	−4.64	157	3.05
Li I (6707)	0.08	89	1.48
[S II] (6730.78)	−2.87	−6	2.61

The mean radial velocity of V565 Mon, computed by the six strongest absorption lines, is $+34 \pm 14$ km s^{-1}. Considering our spectral resolution and the probable blending of several lines, such an error should be considered small enough. The line widths somewhat exceed the instrumental profile of our system, which confirms their photospheric origin.

4 DISCUSSION AND CONCLUSIONS

First of all, we compared previously obtained estimations of V565 Mon distance and brightness with new data from Gaia Data Release 2 (DR2). The modern distance estimate for V565 Mon, based directly on the newly obtained Gaia parallaxes, is 1150 pc ($\pm$ 91 pc), while the statistical estimation from the Bailer-Jones et al. (2018) catalog is 1122 pc. This value is in accordance with the previous estimates of LDN 1653 distance (see Sect. 1). Brightness of the star also did not change in a noticeable way.

For the evaluation of main parameters of V565 Mon, we obtained photometric data for this object with Vizier VO tools, including the photometry from IRAS and AKARI all-sky surveys (Abrahamyan et al. 2015), WISE survey (Cutri & et al. 2012) also (Fischer et al. 2016), MSX catalog (Egan et al. 2003), 2MASS All-Sky catalog (Cutri et al. 2003; Tian et al. 2017) and Gaia survey (Gaia Collaboration et al. 2018). After making necessary transformations and calculations, we produced the spectral energy distribution (SED) of V565 Mon, which is presented in Figure 4. Of course, one should keep in mind that at longer wavelengths (e.g. in AKARI data) a significant amount of emission can have extended origin; however, the SED, obtained by us, is more or less consistent with the star, surrounded by a large mass of heated dust, very likely in the form of a circumstellar disk.

The problem of the extinction value for V565 Mon also is important. In any case, since the star is quite visible in the visual range, its extinction cannot be too high. The Gaia DR2 extinction value for V565 Mon is $A_G = 2.7$. Using visible magnitude of V565 Mon ($V = 13.72$) from the Herbig & Bell (1988) catalog and distance of the star (estimated using Gaia DR2), we found $M_V = 3.05$. Comparing this value with standard M_V for a G0 type main sequence star (Allen 1975), for extinction value one can obtain $A_V = 1.4$. Of course, in case of V565 Mon this value must be higher, because V565 Mon is definitely located above the main sequence.

As can be seen from the SED, V565 Mon emits in the mid and far IR range at least the same, or even a higher amount of energy, as in the optical range. To estimate its total luminosity, we tried several approaches. By integrating the SED curve of V565 Mon we obtained $L_{V565} \approx 130\,L_\odot$ for its bolometric luminosity. But even this value is only its lower limit, since, judging by the SED, the star should emit significant energy up to the submillimeter range. By the equation, suggested for IR sources observed by IRAS (Connelley et al. 2007), we find only 75 $L_\odot$, which in our case can be considered only as an additional correction, to take into account the furthest IR range. We also tried to approximate the SED by Robitaille models (Robitaille et al. 2007), but were not satisfied by any of the solutions, because they cannot represent the nearly flat far-IR side of the SED well. The possible reason for this can be significant extended emission in the far-IR range, but the available data do not allow us to check its existence.

Taking 130 $L_\odot$ as an initial estimate for the V565 Mon bolometric luminosity and making the assumption that the flux in all observed ranges is a result of the radiation of a G0 type central star, we can use general equations like

$$M_{\mathrm{bol},\star} - M_{\mathrm{bol},\odot} = -2.5\log_{10}(L_\star/L_\odot) \qquad (1)$$

and

$$m - M = 5\mathrm{log d} - 5 + A_v \qquad (2)$$

to convert the bolometric luminosity of V565 Mon to absolute magnitude. As a result we ascertain $M_{\rm bol}= -0.58$. We have to add the bolometric correction, which for the G0 star is rather small (Allen 1975), hence, $M_V= -0.55$. We know the observed visible magnitude of V565 Mon ($m = 13.72$, see above), so from Equation (2) the value of extinction for V565 Mon should be $A_V = 2.86$. The similarity of this result with the Gaia estimate is remarkable. One can assume that $A_V \approx 3$ is a reasonable estimate for the V565 Mon extinction.

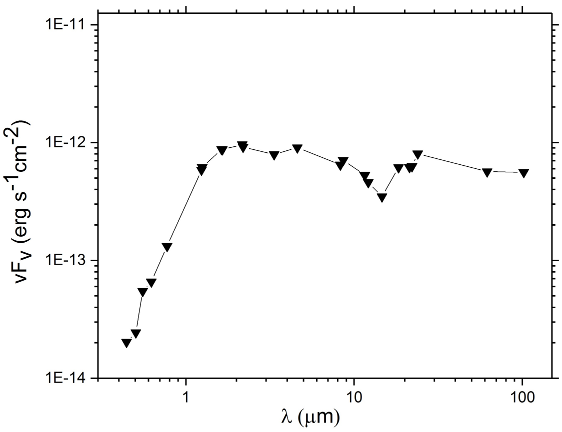

Fig. 4 SED of V565 Mon.

It is obvious that V565 Mon is indeed located in the LDN 1653 cloud, because our estimate of its radial velocity is in a perfect accordance with a velocity (converted to heliocentric) of $+29$ km s^{-1}, measured by the ^{13}CO line (Kim et al. 2004).

Thus, we see that all main features of V565 Mon, described above, point to the PMS nature of this star. However, it is not too easy to classify this object, because its significant luminosity (higher than a great majority of T Tau stars) suggests that it has intermediate mass and, consequently, belongs to the HAeBe star class. On the other hand, its spectral type is probably too late for such classification and its spectrum corresponds to T Tau stars. Nevertheless, V565 Mon could belong to some intermediate class between T Tau and HAeBe stars.

However, the most unusual feature of V565 Mon is the presence of two strong $\lambda6141.71$ and $\lambda6496.89$ BaII absorption lines in its spectrum. Although this fact was mentioned in the Herbig-Bell catalog (Herbig & Bell 1988), nowhere was stressed the peculiarity of barium overabundance in such a young star. Meanwhile, though it is assumed that for low and intermediate ($1\,M_\odot \leq M \leq 3\,M_\odot$) mass stars barium emerges through s-process, recent studies have found the distinct excess of barium abundance in young stellar clusters (D'Orazi et al. 2009; Desidera et al. 2011; Maiorca et al. 2011; D'Orazi et al. 2012; Mishenina et al. 2013). The main trend, described in these works, is in favor of the anticorrelation between barium enrichment and the age of the cluster. In more recent work of Mishenina et al. (2015), new mechanisms of barium enrichment in young open clusters were suggested. Some possible explanations of barium abundance linked it to chromospheric activity, however significant correlation was not detected (D'Orazi et al. 2017). Despite all these various approaches, the processes producing barium in young stars still are hardly understandable.

The most obvious difference of V565 Mon with these studies listed above is that even the youngest open clusters described in these works have ages of 10^8 years, while the age of V565 Mon cannot exceed several million years. On the other hand, EW of BaII line (1.06) is even larger than the upper limit of the curve of growth from the work of Mishenina et al. (2015) (see their fig.1). We screened the spectra of several hundred PMS stars from the Cohen and Kuhi atlas (Cohen & Kuhi 1979) but did not found any object with similar strength of BaII lines.

Besides, we also considered the possibility that a V565 Mon star can be an FU Ori-like object. Actually, this possibility was the reason why we included this star in our observational program. The spectral type of V565 Mon and the scarcity of emission lines in its spectrum are in favor of the FUor hypothesis. Also, it is well known that the existence of Ba II (especially $\lambda6497$) lines is one of the most typical features in spectra of FUors. However, there are several reasons against such a suggestion, in particular: the photospheric absorption lines definitely are wider than in bona fide FUors and FU Ori-like stars; the Hα profile does not show characteristic wide P Cyg type absorption; radial velocities of all absorptions, including even the NaD doublet, are positive, i.e. indicate the absence of significant outflowing activity. Of course, one cannot exclude the possibility that V565 Mon can represent some non-typical case of FU Ori-like stars, or that its spectral characteristics are due to its orientation with respect to the line of sight.

Anyway, for the last 25 years little study was carried out to reveal the nature of V565 Mon. A few previous spectral investigations give only a general view, without going into details. Scarce photometric data that we have in hand also give a very generic and not a complete picture, which does not allow us to draw a conclusion about the variability of V565 Mon. Meanwhile, as our spectral study revealed, this somewhat neglected object could be an important step in understanding the nucleosynthesis problems in young stars. In this sense, the case of V565 Mon is unique and it deserves a detailed high resolution spectral study in the optical and near-IR range.

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References

Abrahamyan, H. V., Mickaelian, A. M., & Knyazyan, A. V. 2015, Astronomy and Computing, 10, 99

Afanasiev, V. L., & Moiseev, A. V. 2005, Astronomy Letters, 31, 194

Allen, C. W. 1975, Astrophysical Quantities (3rd ed.; Athlone: London)

Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., et al. 2018, AJ, 156, 58

Cohen, M. 1974, PASP, 86, 813

Cohen, M., & Kuhi, L. V. 1979, ApJS, 41, 743

Connelley, M. S., Reipurth, B., & Tokunaga, A. T. 2007, AJ, 133, 1528

Cutri, R. M., & et al. 2012, VizieR Online Data Catalog, II/311

Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, VizieR Online Data Catalog, II/246

Desidera, S., Covino, E., Messina, S., et al. 2011, A&A, 529, A54

D'Orazi, V., Magrini, L., Randich, S., et al. 2009, ApJL, 693, L31

D'Orazi, V., Biazzo, K., Desidera, S., et al. 2012, MNRAS, 423, 2789

D'Orazi, V., De Silva, G. M., & Melo, C. F. H. 2017, A&A, 598, A86

Egan, M. P., Price, S. D., Kraemer, K. E., et al. 2003, VizieR Online Data Catalog, V/114

Fischer, W. J., Padgett, D. L., Stapelfeldt, K. L., & Sewiło, M. 2016, ApJ, 827, 96

Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, A&A, 616, A1

Herbig, G. H. 1964, AJ, 69, 141

Herbig, G. H., & Bell, K. R. 1988, Third Catalog of Emission-Line Stars of the Orion Population: 3: 1988 (Santa Cruz: Lick Observatory)

Hilton, J., & Lahulla, J. F. 1995, A&AS, 113, 325

Hoffmeister, C. 1968, Astronomische Nachrichten, 290, 277

Kim, B. G., Kawamura, A., Yonekura, Y., & Fukui, Y. 2004, PASJ, 56, 313

Lyubimkov, L. S. 2016, Astrophysics, 59, 411

Maddalena, R. J., Morris, M., Moscowitz, J., & Thaddeus, P. 1986, ApJ, 303, 375

Magakian, T. Y. 2003, A&A, 399, 141

Magakian, T. Y., Movsessian, T. A., & Nikogossian, E. G. 2008, Astrophysics, 51, 7

Maiorca, E., Randich, S., Busso, M., et al. 2011, ApJ, 736, 120

Mishenina, T., Korotin, S., Carraro, G., et al. 2013, MNRAS, 433, 1436

Mishenina, T., Pignatari, M., Carraro, G., et al. 2015, MNRAS, 446, 3651

Neckel, T., & Staude, H. J. 1984, A&A, 131, 200

Parsamian, E. S. 1965, Izvestiya Akademiya Nauk Armyanskoi, 18, 146

Robitaille, T. P., Whitney, B. A., Indebetouw, R., & Wood, K. 2007, ApJS, 169, 328

Takeda, Y., & Kawanomoto, S. 2005, PASJ, 57, 45

Tian, H.-J., Gupta, P., Sesar, B., et al. 2017, ApJS, 232, 4

Weintraub, D. A. 1990, ApJS, 74, 575