Variability of Hot Post-AGB Star IRAS 19336–0400 in the Early Phase of its Planetary Nebula Ionization

V.P. Arkhipova, M.A. Burlak, V.F. Esipov, N.P. Ikonnikova*, G.V. Komissarova
Moscow State University, Sternberg State Astronomical Institute, Moscow

Abstract

We present photoelectric and spectral observations of a hot candidate protoplanetary nebula – early B-type supergiant with emission lines in spectrum – IRAS 19336–0400. The light and color curves display fast irregular brightness variations with maximum amplitudes $\Delta V = 0^{m}.30$, $\Delta B = 0^{m}.35$, $\Delta U = 0^{m}.40$ and color-brightness correlations. By the variability characteristics IRAS 19336–0400 appears similar to other hot protoplanetary nebulae. Based on low-resolution spectra in the range $\lambda 4000-7500$ Å we have derived absolute intensities of the emission lines $H\alpha$, $H\beta$, $H\gamma$, [SII], [NII], physical conditions in gaseous nebula: $n_e = 10^{4}$ cm$^{-3}$, $T_e = 7000 \pm 1000$ K. The emission line $H\alpha$, $H\beta$ equivalent widths are found to be considerably variable and related to light changes. By $UBV$–photometry and spectroscopy the color excess has been estimated: $E_B-V=0.50–0.54$. Joint photometric and spectral data analysis allows us to assume that the star variability is caused by stellar wind variations.

Key-words: proto-planetary nebulae, photometric and spectral observations, light variability

* Send offprint requests to: ikonnikova@gmail.com

Introduction

According to our current knowledge, after the superwind has ceased, a star with a main sequence initial mass between 1 and 8 $M_\odot$ departs from the tip of the asymptotic giant branch (AGB) leaving a carbon-oxygen core with a mass of 0.5–0.8 $M_\odot$ surrounded by extended gaseous nebula imitating the supergiant characteristics (luminosity, gravitational acceleration). The object is also surrounded by a dust shell becoming optically thinner as expanding. Theoretical calculations predict the star to evolve through the post-asymptotic (post–AGB) phase, with its bolometric luminosity being constant while its radius shrinking and effective temperature rising. When the temperature is high enough ($T_{eff} \approx 20\ 000$) to ionize the circumstellar nebula, there appear emission lines, and the object becomes detectable by spectral sky surveys owing to the presence, first of all, of $H\alpha$ emission line. Hot post–AGB stars, or proto-planetary nebulae (PPNe), are the immediate progenitors of the central stars of planetary nebulae (CSPN).

Hot candidate PPNe possess dust shells with temperatures 100 K < $T_{dust}$ < 250 K, display spectra of early B–type with signs of a supergiant and emission lines, and are usually located outside the Galactic plane.

The object IRAS 19336–0400 ($\alpha = 19^{h}36^{m}17^{s}.5; \delta = -03^{\circ}53'25''.3$ (2000)) totally satisfies all these requirements. The source is located at high galactic latitude ($b = -11^{\circ}.75$) far from star formation regions.

The star was first identified in the survey of Stephenson and Sanduleak (1977) as an object with $V = 12^{m}.5$, OB–type spectrum, $H\beta$ emission and was designated as SS 441. Later Downes and Keyes (1988) examined its optical spectrum in the range $\lambda 3700–7500$ Å in more detail and pointed out the presence of strong Balmer lines, low excitation forbidden lines of [OII], [NII], [SII] and the absence of HeI, HeII and [OIII] lines. The authors estimated the general appearance of the spectrum to be consistent with the class BQ[ ].

IRAS mission measured the flux from SS 441 in far-infrared region (12 – 100 $\mu$m) emitted by cold dust with $T_{dust} = 175$ K (Preite-Martinez, 1988). In IRAS Catalogue the object was designated as IRAS 19336–0400 and based on its location in the IR color-color diagram [12]–[25], [25]–[60] Preite-Martinez put it into the catalogue of possible planetary nebulae.

The object was detected in radio emission at 6 cm (Van de Steene and Pottasch 1995). After Van de Steene et al. (1996) had described its optical spectrum and analyzed IR and radio observations the object was included by Kohoutek (2001) into the catalogue of planetary nebulae under the name of PN 034–11.1.

Analyzing IRAS 19336–0400 spectrum in the range 5 – 40 $\mu$m obtained by Spitzer Space Telescope (Cerrigone et al. 2009) allowed to conclude that the object’s dust shell had mixed carbon–oxygen chemistry, since the spectrum displayed both a broad 10 $\mu$m feature attributed to the SiO molecule and 6.2
and 7.7 \mu m details due to polycyclic aromatic hydrocarbons (PAHs). A possible reason for the mixed chemistry may be binarity that favors the formation of circumstellar disk with crystalline silicates after the star has been enriched with carbon on AGB (Bregman et al. 1993, Waters et al. 1998).

All the data available up to the beginning of our research indicated that IRAS 19336–0400 belongs to the objects in post–AGB evolutionary stage. Hot PPNe in the early phase of envelope ionization are known to display activity in the form of photometric and spectral variability (Arkhipova et al. 2006). We hoped to detect such variability in the IRAS 19336–0400 behavior, and for this purpose we carried out photometric and spectral observations for several years. Hitherto there was no published information concerning photometric behavior of the star, and there existed discrepant data on emission line absolute intensities.

In 2006 IRAS 19336–0400 was included into the hot PPNe variability search and study programme being executed in SAI for more than 20 years. As a result of $UBV$–observations there has been reliably detected fast light variability, and one chapter of the current paper is devoted to its analysis.

Spectral investigations of the star based on the observations that we carried out with 125–cm telescope at SAI Crimean Laboratory in 2008–2011 allowed us to measure emission line absolute fluxes, to derive physical conditions in the nebula, to detect emission line equivalent widths variations. And also we compared our spectral observations with the data of other researchers.

$UBV$–observations of IRAS 19336–0400

In 2006 we started systematic photometric observations of IRAS 19336–0400. Measurements were carried out on the 60–cm telescope Zeiss–1 at SAI Crimean Station with the use of photoelectric $UBV$–photometer constructed by V.M. Lyuty (1971). Photometric system of the photometer is close to that of Johnson. $UBV$–magnitudes of the comparison star HD 184790 ($V = 8.\,^m125, B = 8.\,^m293, U = 7.\,^m966$) were taken from Crawford et al. (1971). For IRAS 19336–0400 the precision of observations of $\sigma \sim 0.\,^m2$ was obtained for each of three filters.

In six years of observations we got 155 brightness estimates for IRAS 19336–0400. Fig. 1 shows light and color curves of the star for the period 2006–2011. The star displays fast irregular brightness and color variations with maximum amplitudes $\Delta V = 0.\,^m30, \Delta B = 0.\,^m35, \Delta U = 0.\,^m40, \Delta (B–V) = 0.\,^m15, \Delta (U–B) = 0.\,^m25$. Light variability may be considered real since $3\sigma$–threshold is exceeded several times. According to our measurements the average brightness values of IRAS 19336–0400 in 2006–2011 turn out to be $< V >= 13.\,^m15, < B >= 13.\,^m47, < U >= 12.\,^m72$. In 2011 (JD 2455715–2455795) the light variation amplitude did not exceed $0.\,^m2$ in all bands.

The character of IRAS 19336–0400 light variations can be traced by observations obtained during three moonless seasons in 2008, when the star was measured almost every night. Fig. 2 shows the light curves of the star in the time interval JD 2454646-2454717. According to these observations the star brightness changes regularly from night to night with characteristic time from 7 to 13 days in different seasons. We failed to determine period both in the total data set and in the subsets of single seasons.

To explain the photometric instability of IRAS 19336–0400 we consider two hypotheses, variable stellar wind and/or pulsations, assumed by Handler (2003) to be the most likely reasons for the group of "cold" central stars of young planetary nebulae — ZZ Lep–type variables, whose photometric variability is similar to that of some hot post–AGB stars.

We have analyzed color–magnitude diagrams including the total set of IRAS 19336-0400 observations (Fig. 3). Colors correlate with brightness, $B–V$ increasing and $U–B$ decreasing when the star is getting brighter. Such a color behavior can not be explained by the temperature variations due to pulsations when brightening is followed by both colors, $U–B$ and $B–V$, becoming bluer. ZZ Lep is also observed to be redder in $B–V$–color when brighter (Handler 2003).

On the other hand Boyarchuk and Pronik (1965) pointed out for Be stars (star+gaseous envelope system) that the envelope radiation always increases $B–V$ and decreases $U–B$ simultaneously.

It's natural to suppose that, if the star brightens because of the stellar wind enhances, and thus the envelope radiation increases its contribution primarily to the hydrogen continuum, then $B–V$ should increase and $U–B$ should decrease.

Accordingly to its spectral type B1I (Vijapurkar et al. 1998) we have assumed for IRAS 19336–0400 normal color $(B–V)_0 = -0.19$ in the calibration of Straizys (1982) and defined the extinction value $E_{B–V} = 0.50 \pm 0.07$. It’s worth mentioning that correcting the mean color $U–B = -0.75$ with the obtained value of $E_{B–V}$ leads to $U–B = -1.15$ that is 0.15 smaller than $(U–B)_0 = -1.0$ for a B1–supergiant. So there exists an appreciable excess of radiation in U–band that argues in favor of the
assumption of additional Balmer continuum emitted by a gaseous envelope.

We have examined separately two–color \((U – B)\), \((B – V)\) diagram for the observations of 2008, the light curves for which are presented in Fig. 2. In Fig. 4 we plot colors of the star both observed and corrected for interstellar reddening with \(E_{B-V} = 0.50\). There are also shown the sequence of supergiants and theoretical \((U – B)\)–\((B – V)\) relations for optically thin in Balmer continuum hydrogen plasma with \(n_e = 10^{40} \text{cm}^{-3}\) and \(T_e = 10000 \text{K}\) and for plasma with \(T_e = 15000 \text{K}\) and variable optical thickness in Balmer continuum taken from Chalenko (1999). One can see that almost all point corrected for reddening lie above the sequence of supergiants and the star oscillation on the diagram upwards to the right and downwards to the left is broadly in line with the direction of hydrogen continuum opacity change probably associated with stellar wind density variability.

We consider unsteady stellar wind to be the main cause of photometric variability. Its origin is to be associated with density inhomogeneities in the outer levels of the star, a low mass supergiant passed through the stage of hydrogen and helium burning on AGB.

Photometric variability of IRAS 19336–0400 appears very similar to that of other hot post–AGB stars. As we reported previously (Arkhipova et al. 2006), B–supergiants with IR–excess: V886 Her, LS IV –12°111, V1853 Cyg, IRAS 19200+3457 and IRAS 07171+1823 also display fast irregular photometric variability with amplitudes of \(0.\text{m}2 – 0.\text{m}4\) in \(V\)–band and color–brightness correlations analogous to IRAS 19336–0400.

For four of the six hot PPNs mentioned above (except for IRAS 19200+3457 and IRAS 19336–0400) there exist spectra of high resolution that allowed to detect P Cyg profiles of HeI and HI recombination lines indicating mass loss in the stars. In the cases when spectral monitoring was carried out (i.e. for V1853 Cyg) significant variability of HeI \(\lambda6678\) line profile and variability of atmospheric absorption line radial velocities was found (García-Lario et al. 1997).

**Spectral observations of IRAS 19336–0400**

Earlier the optical spectrum of IRAS 19336–0400 was investigated several times. Carrying out spectral observations for objects with Hα emission Downes and Keyes (1988) obtained for IRAS 19336–0400 a low resolution \((\sim 13\text{Å})\) spectrum where one could see a featureless slightly red sloping continuum typical for a B–class star and forbidden emission lines of [OII] \(\lambda3727\), [NII] \(\lambda6584\), [SII] \(\lambda6717, 6731\), found in low excitation PNe. Later performing the project to identify new PNe Van de Steene et al. (1996) measured emission line fluxes and estimated the value of interstellar extinction \(A_V = 1.7\). Higher resolution \((\sim 8\text{Å})\) allowed the authors to identify weak absorption lines of CIII \(\lambda4648\), Na I, He I. The object was confirmed to be a PN with a B–type central star. Vijapukar et al. (1998), Parthasarathy et al. (2000) specified the central star spectral type (B1Iapec) and confirmed low excitation of the nebula. Having measured emission line intensities Pereira and Miranda (2007) derived interstellar extinction, electron temperature and density in the nebula, some relative abundances (N,O,S) and based on the results suspected IRAS 19336–0400 to belong to type III PNe according to the classification of Peimbert (1990).

We observed IRAS 19336–0400 spectroscopically in 2008–2011 at the 125–cm reflector of SAI Crimean Station. We used a diffraction spectrograph with 600 lines/mm grating. The slit width was \(4''\).

The detector was a ST–402 CCD \((765 \times 510 \text{ pixels of } 9 \times 9\mu\text{m})\). Spectral resolution (FWHM) was \(7.4 \text{Å}\) in the spectral range of \(4000-7200\text{Å}\).

The spectra were reduced using the standard CCDOPS program and also the program SPE created by S.G. Sergeev at Crimean Astrophysical Observatory. To calibrate fluxes the spectra of standard stars were observed: 18 Vul, 4 Aql, κ Aql. Absolute spectral energy distributions for standard stars were taken from electronic versions of spectrophotometric catalogues (Glushneva et al. 1998, Kharitonov et al. 1988, Alekseeva et al. 1997). It’s worth mentioning that the discrepancy of data for the same spectrophotometric standard stars between different catalogues is about 10% and it is especially significant in the blue range. While calibrating spectra we did not take into account the air mass difference between the program star and the standard star though sometimes it was equal to 0.4. Besides on some nights the weather was instable. Therefore after the primary calibration by standard star spectra we then adjusted derived spectral energy distributions to photometric data obtained on the same nights.

Fig. 5 shows the spectrum of IRAS 19336–0400 obtained on July 4, 2008. One can easily see emission lines of hydrogen, [NII], [SII], [OI], generated in the nebula and superposed on the slightly red sloping continuum of the central star with faint absorption lines of HeI \(\lambda4921, \lambda5876, \lambda6678\) and \(\lambda7065\), the absorption lines of NaI \(\lambda5892\) and CIII \(\lambda4648\) are also present.
We have measured absolute fluxes of nebula emission lines by integration over line profiles. Measuring uncertainties come from natural noise, instrumental errors, calibration errors, uncertainty of the underlying continuum position. We estimate the intensity error to be about 10% for stronger lines and about 30% for [NII] \( \lambda 6575 \). Our accuracy and spectral resolution appeared insufficient to investigate absorption lines behavior.

Table 1 lists observed relative emission line intensities scaled to \( F_{H\beta} = 100 \), absolute intensity of H\( \beta \) line and the [SII] line intensities ratio \( R(\text{SII}) = \frac{\lambda 6717}{\lambda 6731} \), obtained in this work and averaged over the observation period and the quantities found by Van de Steene et al. (1996) and by Pereira, Miranda (2007). Van de Steene et al. (1996) did not give explicitly the measured absolute H\( \beta \) intensity but in the paper there is a graphical spectrum presentation in absolute energy units that allowed us to assess the required quantity for comparison. Our intensities both relative and absolute are in reasonable agreement with those of Van de Steene et al. (1996). The same is true for relative intensities given by Pereira, Miranda (2007) but not for the absolute ones: both H\( \beta \) line intensity and the continuum level obtained in our study are 4–5 times higher than that from Pereira, Miranda (2007). If we managed to carry out both photometric and spectral observations simultaneously, we adjusted the calibration of our spectra to \( B \) and \( V \) magnitudes of IRAS 19336–0400 obtained on the same nights. The absolute fluxes of Pereira, Miranda (2007) seem too low even if to take into consideration light variability of IRAS 19336–0400 and calibration errors.

From the intensity ratio for the first two Balmer lines we estimated the interstellar extinction for IRAS 19336–0400 assuming the dereddened decrement from Hummer, Storey (1987) (H\( \alpha \)/H\( \beta \) = 2.9 for \( n_e = 10^4 \, \text{cm}^{-3} \), \( T_e = 7.5 \times 10^4 \, \text{K} \) and the extinction law of Seaton (1979). The value of \( c_{\text{H}\beta} \), characterizing the interstellar extinction in H\( \beta \) line and referred to color excess as \( c_{\text{H}\beta} = 1.47 E_{B-V} \), appeared to be 0.8 and in good agreement with the results of Van de Steene et al. (1996) and also of Pereira, Miranda (2007) with some remarks (Table 1).

From the intensity ratios of forbidden lines \( R(\text{SII}) = \frac{\lambda 6717}{\lambda 6731} \) and \( R(\text{NII}) = \frac{\lambda 6548 + \lambda 6584}{\lambda 5755} \) we have derived the values of electronic temperature and density in the nebula (Table 1) that are close to the quantities of Pereira, Miranda (2007). \( R(\text{SII}) \) value is close to the limit one, attained at high density, therefore our \( n_e \) estimate is valid only up to an order of magnitude.

Firstly we planned to study the spectral variability of IRAS 19336–0400 and its relation to the photometric variability. The emission component of IRAS 19336–0400 optical spectrum consists of several nebula lines weak enough, relative to the stellar continuum, to affect the summary brightness in \( UBV \)-bands. So one may assume that calibration by photometry does not prevent from detecting emission line variability. But during four years of observations we did not detect emission line intensity variations beyond the bounds of error. It may be explained by the fact that fast irregular variability of the central star barely affects the emission line spectrum generated in the gaseous nebula. Thereby we consider the summary spectrum of IRAS 19336–0400 to consist of constant emission component, related to the young PN, and variable continuum of the central star.

To detect continuum variability and to exclude errors arising from calibration we studied how the equivalent widths of H\( \alpha \) and H\( \beta \) emission lines vary in relevance to the star \( B \) and \( V \) brightness and we found inverse correlation between the equivalent widths of given lines and brightness: the widths appear to be smaller when the star is brighter. Fig. 6 shows the results of simultaneous spectral and photometric observations (10 nights).

The detected correlation of brightness and H\( \alpha \) and H\( \beta \) equivalent widths may be explained in the following way: the star brightens because mass outflow rate increases and the contribution of stellar wind radiation to the total continuum luminosity becomes more prominent. The emission line equivalent widths are the largest when the wind continuum contribution to the total continuous spectrum is rather small (the star is faint). If the mass outflow rate increases (the star is bright) then the continuum emission of the wind raises the total continuum level and the emission line equivalent widths decrease.

**Conclusions**

The photometric and spectral monitoring of the hot PPN IRAS 19336–0400 allowed to detect light and spectral variability of the star.

Fast night to night irregular light oscillations with maximum amplitudes of \( \Delta V = 0.3, \Delta B = 0.35, \Delta U = 0.4 \) have been found. In addition the connection between light and colors has been detected: the star brightening is followed by \( U - B \) decreasing and \( B - V \) increasing.

We suppose that photometric variability of the object is caused by the sporadical mass outflow rate
change ($\dot{M}$) appearing as a variable continuum radiation excessive if compared to the spectral energy distribution of a B1–supergiant star. This additional continuum may be fitted by emission of hydrogen gas with electron density $\sim 10^{10}$ cm$^{-3}$ and temperature from 10 000 to 15 000 K.

Color variations also argue in favor of gaseous envelope contribution changes and against temperature variations of the stellar photosphere. To define reliable characteristic times of variability it is necessary to perform photometric observations with better time resolution than ours.

By low-resolution spectral observations of IRAS 19336–0400 Balmer emission line equivalent widths have been found to be variable with time that points out the continuum variability while nebular emission line fluxes remain constant within measuring accuracy. The correlation of star brightness with nebular emission line equivalent widths has been detected. The correlation arises from emission line equivalent widths becoming larger when continuum level is dropping while the star is fading.

IRAS 19336–0400 has become the sixth object in the group of variable B–supergiants with IR–excess along with V886 Her, LSIV–12°111, V1853 Cyg, IRAS 19200+3457 and IRAS 07171+1823. Astonishing similarity in photometric behavior of these stars evidences that they have the common nature of variability.

Treating the variability of IRAS 19336–0400 and other hot PPN candidates we rely on the assumption that during post–AGB evolution, when the star temperature is rising, there starts a new phase of mass loss driven by light pressure in resonance lines (Kwok 1993). The stellar wind of these stars is variable that is evidenced by high resolution spectral data obtained by various researchers for the majority of the sample stars. Spectroscopic observations of the same quality for IRAS 19336–0400 should be invaluable, and it is especially important to study line profiles, to define radial velocities and their relation to the star brightness.

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Figure 1. Light and color curves of IRAS 19336–0400 in 2006-2011.

Figure 2. $U$, $B$, $V$ curves of IRAS 19336–0400 in the range JD 2454646-2454717.
Figure 3. Color–magnitude diagrams.

Figure 4. Two–color diagram for the observations presented in Fig. 2. Colors of IRAS 19336–0400, observed and corrected with $E_{B-V} = 0.5$, are shown by points and open circles, respectively. This diagram also displays the supergiant sequence and theoretical $(U - B), (B - V)$ relations for emitting plasma optically thin in Balmer continuum with $T_e = 10,000$ K, $n_e = 10^{10}$ cm$^{-3}$ (curve 1) and optically thick with $T_e = 15,000$ K (curve 2) from Chalenko (1999).
Figure 5. IRAS 19336–0400 spectrum obtained on July 4, 2008.

Figure 6. Relations between Hα and Hβ emission line equivalent widths and brightness in B and V–bands.
Table 1: Relative observed spectral line intensities scaled to $F_{\text{H}\beta} = 100$ and physical conditions for IRAS 19336–0400.

| Parameters                | This paper | Van de Steene et al. (1996)* | Pereira and Miranda (2007) |
|---------------------------|------------|------------------------------|----------------------------|
| $F_{\text{H}\beta} \times 10^{13}$, erg/cm$^2$/s | 8.75       | –                           | 1.8                        |
| 4340                      | 33         | 35.6                        | 33                         |
| 5755                      | 1.4        | 1.8                         | 2.5                        |
| 6548                      | 92         | 98                          | 82.7                       |
| 6563                      | 510        | 516                         | 578                        |
| 6584                      | 261        | 250.5                       | 300                        |
| $R(S\text{ II})$          | 0.5        | 0.5                         | 0.5                        |
| $c_{\text{H}\beta}$      | 0.8        | 0.8                         | –                          |
| $E_{B-V}$                 | 0.54       | 0.54                        | 0.55**                     |
| $T_e$, K                  | $7000^{\pm 2500}_{1000}$ | –          | $7600 \pm 600$            |
| $n_e$, cm$^{-3}$          | $\sim 10^4$ | –                          | $13000 \pm 3600$          |

* The paper contains line intensities corrected for interstellar reddening; we have recalculated them back to the observed ones using the extinction law of Whitford (Seaton, 1979) and $c_{\text{H}\beta}$ value obtained by the authors themselves.

** Pereira and Miranda (2007) adduce $E_{B-V}$ value without mentioning what extinction law has been used; applying that of Seaton (1979) for $\text{H}_\alpha/\text{H}_\beta = 5.78$ ratio gives $E_{B-V} = 0.63$. 