K-band spectra of selected post-AGB candidates

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Original Article

Received: 6 May 2020 / Accepted: 6 July 2020 / Published online: 17 July 2020
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Abstract We present medium resolution (1000) K-band spectra of 12 post-AGB candidates and related stars. For several objects in our sample, these spectra were obtained for the first time. The Br\(\gamma\) line in emission is detected in seven objects indicating the onset of photo-ionization in these objects. Four objects show the presence of an He I line. We detect H\(_2\) emission line in the spectra of IRAS 06556+1623, IRAS 22023+5249, IRAS 18062+2410 and IRAS 20462+3416. The H\(_2\) emission line ratio 1-0 S(1)/2-1 S(1) indicates that H\(_2\) is radiatively excited due to the UV radiation of hot post-AGB central stars. When compared with the recent observations by other investigators, the Br\(\gamma\) and H\(_2\) emission fluxes varied in some of the objects. The hot post-AGB stars IRAS 22495+5134, IRAS 22023+5249, IRAS 18062+2410 and IRAS 20462+3416 seem to be evolving rapidly to the young low excitation planetary nebula phase. The spectra of the objects presented in this paper may be useful for future observers as some of these stars show spectral variation and since the post-AGB evolution of some of these stars is relatively rapid.

Keywords Stars: AGB and post-AGB · Stars: circumstellar matter · Stars: evolution · Stars: mass-loss · Infrared: ISM

1 Introduction

The early stage of post Asymptotic Giant Branch (post-AGB) stars is marked by the spectral types typically from K I to F I type supergiants. Their ejected envelopes expand and can be seen in the scattered stellar light and in molecular lines such as H\(_2\) and CO. They mimic the spectra of supergiants because of their extended atmospheres. As the cool post-AGB objects evolve they will be hot post-AGB stars of the spectral types A I to OB I supergiants. They are rapidly growing hotter due to their gravitational contraction as they evolve on the post-AGB evolutionary track towards young planetary nebulae (PNe) stage (Parthasarathy and Pottasch 1986, 1989). The UV radiation of the post-AGB star causes photoionization of the envelope and the spectrum shows recombination lines and collisionally excited lines. Parthasarathy (1993a) listed several cool and hot post-AGB candidates based on their IRAS colors and flux distribution. Among those post-AGB objects which have far-IR colors similar to PNe, several proto-PNe with hot (O I to B I type) stars were detected (Parthasarathy et al. 2000b). The UV spectra of some of these objects show violet shifted stellar wind P-Cygni profiles indicating hot and fast radiatively driven stellar winds. Multi-wavelength studies of these objects enabled us to further understand the evolution of their circumstellar envelopes and that of the central stars.

Near-Infrared (Near-IR), medium resolution (~1000) spectroscopy in K-band (from 2–2.4 \(\mu\)m) is quite useful and a convenient tool to study these objects as it covers a range of emission spectra to trace their molecular and the ionized envelopes. The excitation and ro-vibrational transitions of molecular hydrogen (at 2.1218, 2.2477, 2.2233, 2.2014 and 2.1542 \(\mu\)m) and the recombination lines of hydrogen (Br\(\gamma\) line at 2.166 \(\mu\)m) and of helium (He I line at 2.058 \(\mu\)m) are present in near-IR spectrum. Gledhill and Forde (2015) give the spectral features and their wavelengths in the K-band spectra of several hot post-AGB stars. They carried out integral field spectroscopy of hot post-AGB stars with near-infrared Integral Field Spectrometer (NIFS) instrument on Gemini North. It provided much higher resolution and much
better sensitivity, and spectral images. They made observations in 2007 and have three sources in common with the present study. Their work revealed spatial extent of the emission line regions in those three objects (see Sect. 3, Fig. 1, Table 1).

Emission line ratios of different transitions of H$_2$ (1-0 S(1)/2-1 S(1) and 1-0 S(1)/3-2 S(3)) give a clue on the dominant excitation mechanism of H$_2$, i.e. due to fluorescence by the UV radiation from the central star or thermally by shocks. While the emission lines of H$_2$ (and also CO lines at 2.2935 µm and 2.322 µm) help us to trace the molecular gas, Br$\gamma$ and He I emission lines come from the recombination spectra of ionized hydrogen and singly ionized helium respectively and hence they trace the ionized gas in the nebula. Br$\gamma$ emission traces the ionized hydrogen gas better than the optical lines as the optical lines suffer high extinction due to the presence of thick circumstellar dust envelopes. Near-infrared spectra of post-AGB stars (proto-planetary nebulae PPNe) was studied by Hrivnak et al. (1994), Oudmaijer et al. (1995), Garcia-Hernandez et al. (2002), Kelly and Hrivnak (2005) and Gledhill and Forde (2015). The observations reported here were made in October 1999 and are similar in sensitivity and resolution to observations made by Garcia-Hernandez et al. (2002). We present here K-band medium resolution (1000) spectra of 12 selected post-AGB candidates (nine are hot stars and three are cool stars).

### 2 Observations

The observations were made with the 188-cm telescope of the Okayama Astrophysical Observatory (OAO) of the National Astronomical Observatory of Japan (NAOJ) and the Okayama Astrophysical System for Infrared Imaging and Spectroscopy OASIS (Okamura et al. 2000) was used in obtaining the spectra. The OASIS was used in spectroscopic mode and K-band spectra covering the wavelength range 2.0–2.4 µm were obtained during 1999 October 22 to 25. We used 300 lines per mm grating and a slit width of 2.4 seconds of arc. The slit position angle was fixed to East-West. The spectra (Fig. 1) have a resolution of about 1000. We obtained spectra of rapidly rotating B and A type stars with no stellar emission lines in their K-band spectra to remove atmospheric absorption lines in the K-band spectra of stars presented in the paper.

Standard process of data reduction was performed with IRAF. The wavelength calibration was accomplished using the atmospheric OH lines (Olivia and Origlia 1992). The sky background was removed by fitting the spectrum of the sky adjacent to the program star. The final spectra of the program stars are shown in Fig. 1. The line fluxes are measured and are listed in Table 1 along with the emission line ratios of H$_2$ 1-0 S(1)/2-1 S(1). We detected He I line at 2.058 µm for some sources however, full line profile is not recorded to measure the flux. Hence in Table 1 we only indicate if this line is present in the spectrum.

### 3 Notes on individual objects

We discuss here the K-band spectral properties of each post-AGB candidate based on Fig. 1 and Table 1. The spectral types of these 12 objects can be found in SIMBAD (see Table 1).

#### 3.1 IRAS 22495+5134 (M2-54, LS III +51 42)

Optical variations in the brightness and spectrum of IRAS 22495+5134 were studied by Arkhipova et al. (2013, see also Handler 1999). It shows a small amplitude variability in brightness and also variability in the spectrum. We find from our spectrum of this star a strong Br$\gamma$ emission profile showing the developed hydrogen photo-ionization region in the nebula. H$_2$ lines are not detected in our spectrum. It is a young compact planetary nebula. The UV spectrum of IUE and the circumstellar dust characteristics of this object were analyzed by Gauba and Parthasarathy (2003, 2004). From

![Fig. 1 K-band spectra of selected post-AGB candidates](image-url)
the UV spectrum they derive that the central star has a spectral type of O9. This object seem to be evolving rapidly to the planetary nebula phase. H$_2$ emission is not detected in the K-band spectrum of this source (Fig. 1). The central star is hot enough for radiative H$_2$ excitation, but previous studies argued that H$_2$ is expected to be disassociated for hot post-AGB stars unless they have a thick torus region that provides for shielding.

### 3.2 IRAS 06556+1623 (HD 51585)

IRAS 06556+1623 is a high Galactic latitude (b = 8°, 9), with Be I/BQ[ ] spectral type. Parthasarathy and Pottasch (1989) and Parthasarathy (1993a) classified this as a hot post-AGB star based on IRAS colors and flux distribution. Arkhipova et al. (2006) and Jachek et al. (1996) detected optical spectroscopic and photometric variability of this star. We present the K-band spectrum of this object and it shows a strong Br$_\gamma$ in emission which is due to a developed hydrogen photo-ionized region. In short ward of Br$_\gamma$, there seem to be weak emission lines present in the spectrum which could be due to Fe. H$_2$ lines are seen in the spectrum, which are much weaker than Br$_\gamma$ line (Fig. 1). We find that H$_2$ line flux ratios of 1-0 S(1)/2-1 S(1) = 4.73 (Table 1). For a purely UV pumped H$_2$ excitation, this ratio is about 2 (Black and Dalgarno 1976) and it can have a value between 4 to 10 for a shock excitation (Smith 1995). However, for dense gas exposed to intense UV radiation, collisional heating causes this ratio to be little larger than expected from pure UV pumping. Gledhill and Forde (2015) stated in their paper that shocks were not evident in most of their hot post-AGB sources and

### Table 1 Relative Line fluxes

| Object          | Br$_\gamma$ | H$_2$ 1-0 S(1) | H$_2$ 2-1 S(1) | H$_2$ 1-0 S(0) | He I   | 1-0 S(1)/2-1 S(1) | Sp. Type |
|-----------------|-------------|----------------|----------------|----------------|--------|----------------|----------|
| IRAS ID         | 2.166 µm    | 2.1218 µm      | 2.2477 µm      | 2.2233 µm      | 2.058 µm |                 |          |
| 22495+5134      | 93.69       | –              | –              | –              | –      | –              | B0e      |
| 06556+1623      | 55.69       | 2.27           | 0.48           | 0.93           | Yes    | 4.73           | Bet/BQ[ ]|
| 18237-0715      | 18.90       | –              | –              | –              | Yes    | –              | B5/9Iaeq |
| 22023+5249      | 17.84       | 20.69          | 6.85           | 6.62           | No     | 3.02           | B0e      |
| 18062+2410      | 17.24       | 27.18          | 5.56           | 13.48          | –      | 4.89           | B1IHe    |
| 18313-1738      | 11.84       | –              | –              | –              | No     | –              | Be       |
| 20462+3416      | 6.78        | 5.58           | 1.54           | 2.49           | Yes    | 3.62           | B1.5IaIa |
| 20056+1834      | –           | –              | –              | –              | No     | –              | G0Ie     |
| 19399+2312      | –           | –              | –              | –              | No     | –              | B0IVe    |
| 19475+3119      | absorb      | –              | –              | –              | No     | –              | F3Ib     |
| 23304+6147      | absorb      | –              | –              | –              | No     | –              | G2Ia     |
| 05040+4820      | absorb      | –              | –              | –              | No     | –              | A4Ia     |
argued for UV excitation with collisional heating. They also showed line ratio maps that illustrated how the 1-0/2-1 ratio can vary across a source. Garcia-Hernandez et al. (2002) included this star in their IR spectroscopic survey of post-AGB stars and found this ratio to be larger than 1.7. Our K-band spectrum also shows He I line at 2.058 µm indicating singly ionized helium region and a hotter star which is consistent with the presence of a photo-ionized nebula. In the optical spectrum of this star, in addition to nebular emission lines, several Fe lines were observed by Arkhipova et al. (2006).

Figure 2 shows a medium resolution (1000) optical spectrum of IRAS 06556+1623. The optical spectrum of the object was obtained on January 28, 2003 using the OMR spectrograph at the Cassegrain focus of the 2.3-m Vainu Bappu Telescope (VBT) at Kavalur. A dispersion of 2.6 Å per pixel is achieved using a 600 lmm−1 grating. The following lines are seen in the spectrum: H I (4340 Å), [O III] (4363 Å), He I (4388 Å), He I (4472 Å), H I (4861 Å), He I (4922 Å), [O III] (5007 Å), He I (5876 Å), [O I] (6300 Å), [O I] (6364 Å), H I (6563 Å), He I (6678 Å), He I (7065 Å) and [O I] (7325 Å) (see Fig. 2). The presence of [O III] 5007 Å forbidden line in the optical spectrum (Jaschek et al. 1996) indicates that photo-ionization has started. The presence of He I emission lines shows that the central star is of high Teff. This star may have a compact nebula and disc around it. Arkhipova et al. (2006) find small amplitude variation in brightness and variation in the strength of emission lines (see also Jaschek et al. 1996).

### 3.3 IRAS 18237-0715 (MWC 930)

Vijapurkar et al. (1998) presented the low resolution blue spectrum of IRAS 18237-0715 and concluded that it may be a post-AGB star or a Luminous Blue Variable (LBV; see also Parthasarathy et al. 2000b). The stellar spectral type is B5/9 Iaeq. A detailed optical spectroscopic study of this star was made by Miroshnichenko et al. (2005) and they found it to be a new LBV. We present the K-band spectrum of this object for the first time and our spectrum shows P-Cygni type Brγ emission profile showing ongoing mass-loss and few emission lines short ward of Brγ. The Brγ emission indicates the presence of hydrogen photo-ionization region in this object. We also detected He I emission line at 2.058 µm. Our spectrum of this object does not show H2 lines (Fig. 1). The non-detection of H2 could be a sensitivity issue. A high-resolution K-band spectrum with better sensitivity may reveal H2.

### 3.4 IRAS 22023+5249 (LS III + 52 24)

IRAS 22023+5249 is a high velocity hot post-AGB star (Sarkar et al. 2012). From their 2 µm spectral survey, Kelly and Hrivnak (2005) find H2 emission from this object. From our K-band spectrum, we also find H2 emission lines at 2.12-, 2.22- and 2.247 µm (Fig. 1). We also find Brγ emission from this object indicating the presence of low excitation nebula. The Brγ flux is comparable to the flux of H2 at 1-0 S(1) transition. However, no He I line is detected. We find that the H2 1-0 S(1)/2-1 S(1) line flux ratio is 3.02 indicating the excitation mechanism of H2 is due to UV fluorescence. Kelly and Hrivnak (2005) find this ratio to be 2.7, which is in good agreement with our value. Gledhill and Forde (2015) made a detailed study of the 2 µm to 2.4 µm spectrum of this source. They show that the H2 1-0 S(1)/2-1 S(1) ratio has value of 3.41 and also suggested the excitation of H2 can be contributed both by shocks and UV pumping. The IUE UV spectrum and infrared data of the circumstellar dust shell of IRAS 22023+5249 were studied by Gauba and Parthasarathy (2003, 2004). They suggested the presence of a dusty disk around the star. They also find evidence for the presence of hot stellar wind from the IUE spectrum. This object seems to be evolving rapidly towards planetary nebula phase. The star shows small amplitude variability in brightness and also variations in the spectral lines (Arkhipova et al. 2013). Gledhill and Forde (2015) show a map of H2 ratios (see Fig. 9 in their paper), which shows ratios of 5–8 in bubble-like lobes and extended H2 with ratios of three and lower.

### 3.5 IRAS 18062+2410 (SAO 85766)

IRAS 18062+2410 is a high Galactic latitude (b=19°.8) hot post-AGB star. It is a rapidly evolving hot post-AGB star (Parthasarathy et al. 2000a) similar to SAO 244567 (Parthasarathy et al. 1993, 1995) with Be spectral type. Our K-band spectrum appear to some extent similar to that of IRAS 22023+5249. We find H2 emission lines at 2.12, 2.22 and 2.247 µm in our K-band spectrum (Fig. 1). The H2 line flux ratio 1-0 S(1)/2-1 S(1) = 4.89. Kelly and Hrivnak (2005) find from their 2 micron spectral survey that this ratio has a value of 3.8 and also proposed that H2 excitation has both a thermal and a radiative origin. Gledhill and Forde (2015, and the references therein) have made a detailed study of IRAS 18062+2410 using their 2 µm to 2.4 µm spectrum and show that H2 line ratio S (1)/2-1 S(1) = 6.2. Brγ emission shows a P-Cygni profile showing ongoing post-AGB mass-loss, and the presence of this line indicates the onset of photo-ionized hydrogen region. The Brγ flux is smaller than the flux of H2 at 1-0 S(1) transition. The strength of Brγ is variable with time (Garcia-Hernandez et al. 2002). Gledhill and Forde (2015) conclude that there is little evidence for shock structures in this source and that the high 1-0/2-1 ratio came from regions where the gas density and UV intensity are high.
3.6 IRAS 18313-1738 (MWC 939)

Vijapurkar et al. (1998) and also Parthasarathy et al. (2000b) presented the blue spectrum of IRAS 18313-1738. Its spectral type is Be IV and the object is most likely a hot post-AGB star (Parthasarathy et al. 2000b) or a hot sub-dwarf. We present the K-band spectrum of this object for the first time and it also has a hydrogen photo-ionized region as shown by the presence of Brγ emission line. He I line is not present in the K-band spectrum. We do not detect H2 lines in our spectrum. The non-detection could be a sensitivity and resolution issue.

3.7 IRAS 20462+3416 (LS II +34 26)

Parthasarathy (1993b) discovered IRAS 20462+3416 as a hot post-AGB star. From our K-band spectrum we find the presence of H2 lines at 2.12-, 2.22- and 2.247 μm. We also detected Brγ emission (Fig. 1) which shows the presence of hydrogen ionized gas. The Brγ line flux is comparable to the flux of H2 at 1-0 S(1) transition. Gledhill and Forde (2015) carried out a detailed study of the 2 μm to 2.4 μm spectrum of this star and found that the Brγ emission is spatially extended tracing the extended ionized hydrogen region. We also detected HeI line at 2.058 μm. We find from our spectrum that the H2 line flux ratios 1-0 S(1)/2-1 S(1) = 3.62 indicating that the overall excitation of H2 in this object is due to UV fluorescence. This is in agreement with the suggestion by Kelly and Hrivnak (2005) in their H2 2-micron spectral survey of post AGB objects (the ratio given by them is 1.5). However, the line flux ratio derived later by Gledhill and Forde (2015) is 5 ± 2 and argued based on morphology that most of the H2 had been dissociated. Gledhill and Forde (2015) showed two clumps of 1-0 S(1) emission plus what looked like faint emission across the 4′′×4′′ field. Kelly and Hrivnak (2005) showed emission extending 12″ along the 2.4′′ wide E-W slit. Their fluxes were probably dominated by the extended emission which one would expect to be excited radiatively. Our observations could easily be of a different region from the regions that were surveyed in the two papers mentioned above. Garcia-Lario et al. (1997) and Arkhipova et al. (2001) made a detailed study of the optical spectrum of this rapidly evolving hot post-AGB star and found that absorption and emission profiles are variable. This star is evolving rapidly to the young planetary nebula phase (Parthasarathy 1993b, 1994).

3.8 IRAS 20056+1834

The late type variable star IRAS 20056+1834 has a spectral type of G0e. We obtained the K-band spectrum of the star for the first time. No H2 lines and Brγ line are detected in our spectrum (Fig. 1). However, it shows CO (2-0) and CO (3-1) absorption lines at 2.29 μm and 2.32 μm respectively. Menzies and Whitelock (1988) discussed the optical spectrum of this star and later, Klochkova et al. (2007) analyzed repeated high-resolution optical spectrum of this star and found that the photospheric lines are variable. Their chemical composition study of the star shows that it is overabundant in carbon and nitrogen.

3.9 IRAS 19399+2312 (V450 Vul)

IRAS 19399+2312 is a BOIVe type star. It may not be a post-AGB star (see Cerrigone et al. (2009)) however, it is possible that it could be a hot subdwarf. Our K-band spectrum does not show either H2, He I or Brγ emission lines (Fig. 1). The CO absorption lines at 2.2935 μm and 2.322 μm seem to be present.

3.10 IRAS 19475+3119 (HD 331319)

The post AGB star IRAS 19475+3119 is of F3Ibe spectral type (Parthasarathy 1993a). It shows a quadrupolar nebular morphology (Sahai et al. 2007). Hrivnak et al. (1994) have done near-IR spectral study of this cool post AGB star and found Brγ in absorption. Our K-band spectrum indicates a broad Brγ absorption profile with possible weak emission in the wings (Fig. 1). No H2 lines are seen. Kelly and Hrivnak has included this source in their H2 emission survey. They also did not find H2 line. Sivarani et al. (2001) analyzed high-resolution optical spectra of this post-AGB star and derived the stellar atmospheric parameters and found that abundances are due to mixing of third dredge-up, and nitrogen is overabundant.

3.11 IRAS 23304+6147

Klochkova et al. (2000) analyzed high-resolution optical spectrum of this post AGB star. They find the photospheric temperature T_eff of 5900 K and log g = 0.0. They find this object to be a metal poor (Fe/H = −0.6) and show over abundance of carbon and s-process elements. Kelly and Hrivnak (2005) included this object in their 2 μm spectral survey and found Brγ in absorption. They found the spectral class of this object to be G2 Ia. We find from our K-band spectrum of this post-AGB star that the Brγ is a broad absorption feature (Fig. 1). We do not see any H2 lines or a He I line in our spectrum.

3.12 IRAS 05040+4820 (SAO 40039)

Parthasarathy (1993a) classified IRAS 05040+4820 as a post-AGB supergiant based on its IRAS colors and flux distribution. Fujii et al. (2002) made B, V, R, I, J, H, K photometry and studied the flux distribution and derived
the circumstellar dust shell parameters and concluded that it is a low mass post-AGB star. Its spectral type is A4Ia. Parthasarathy et al. (2005) made B, V, R, I polarization observations and concluded that the circumstellar dust shell has asymmetric shape. Our K-band spectrum of this post-AGB star shows that the Brγ is a broad absorption line (Fig. 1). No H2 lines or HeI line are seen in our K-band spectrum for this object.

4 Discussion and conclusions

K-band (2 µm to 2.4 µm) spectra of 12 post-AGB candidates are presented. In our sample seven stars are hot post-AGB stars. Seven objects are found to show Brγ emission lines at 2.166 µm implying ionized hydrogen region in the nebulae. Three sources show Brγ in absorption and three have Brγ P-Cygni profile indicating ongoing mass loss in these objects. Four sources show HeI line at 2.058 µm. H2 2.1218 µm emission line is present in the spectra of IRAS 06556+1623, IRAS 22023+5249, IRAS 18062+2410 (SAO 85766) and IRAS 20462+3416. These four sources also were seen to show variation in Brγ and H2 emission line strengths when compared with other studies mentioned above. Four of the sources show H2 transitions at 1-0 S(1) and 2-1 S(1) (Fig. 1, Table 1). The H2 flux ratio 1-0 S(1)/2-1 S(1) indicates that the dominant excitation of H2 is by UV florescence. The hot post-AGB stars IRAS 22495+5134, IRAS 22023+5249, IRAS 18062+2410 and IRAS 20462+3416 seem to be evolving rapidly to the planetary nebula phase. Further monitoring of stars showing Brγ and H2 emission lines is important. Some of the cooler stars in which the Brγ line is in absorption is most likely stellar photospheric origin. Marquez-Lugo et al. (2013) conclude that H2 emission is not exclusive of bipolar planetary nebulae (PNe) and proto-planetary nebulae (PPNe), although objects with this morphology are still the brightest H2 emitters.

The study of Gledhill and Forde (2015) revealed the spatial extent of the emission line regions in IRAS 18062+2410 (SAO 85766), IRAS 20462+3426 (LS II +34 26), and IRAS 22023+5249 (LS III +52 24). In our study and in our data reduction we have not made an attempt to estimate the expected spatial extent of the sources and how it affected the fluxes measured through the 2.4′′ width E-W slit.

The rapidly evolving hot post-AGB stars mentioned above are of significant importance as these are rare objects and the evolution of their circumstellar envelopes and central stars can be studied in real time. IRAS 18062+2410 (SAO 85766) which is observed by all four of this studies mentioned above and also by Davis et al. (2003) (observed in June 2000) evolved from a 8500 K post-AGB star to 20,000 K post-AGB star in 20 years (Parthasarathy et al. 2000a), and its ionized mass increased by a factor of three in a short span of 8 years (Cerrigone et al. 2011). The Brγ and radio flux increased linearly indicating that the ionization of the circumstellar envelope started around 1990 (see Gledhill and Forde 2015). IRAS 20462+3426, and IRAS 22023+5249 are in similar rapid phase of evolution of their central stars and their circumstellar envelopes. Further K-band spectroscopic monitoring of these rapidly evolving post-AGB objects is needed.

Acknowledgements MP is thankful to Dr. T. Fujii for his help during the observations. MP is thankful to the Director General of NAOJ and Prof. Y. Nakada and Prof. S. Deguchi for their kind encouragement and support. We are thankful to the referee for helpful comments.

Conflict of interest The authors declare that they have no conflict of interest.

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