Asymmetric Planetary Nebulae III
ASP Conference Series, Vol. XXX, 2004
M. Meixner, J. Kastner, B. Balick and N. Soker eds.

The Post-AGB Star IRAS 16594−4656

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Abstract. We present the basic properties of the multipolar post-AGB star IRAS 16594−4656, and discuss in particular its near infrared spectrum which shows shock excited H_2 and [Fe II] emission lines.

1. General Properties

IRAS 16594−4656 is an optically visible post-AGB star, listed in the *USNO* B1.0 catalog with a position $\alpha = 17^h\ 03^m\ 10\overset{s}{.}05$, $\delta = -47^\circ\ 00'\ 27\overset{''}{.}6$ (J2000). In Fig. 1 we show the spectral energy distribution (SED) of this star. It has a double peaked spectrum typical for post-AGB stars. Overplotted is a Kurucz model in the optical and a black body fit of 188 K in the infrared. The spectrum that is shown is significantly reddened by interstellar extinction with $A_V = 7.5 \pm 0.4$ mag and $R_V = 4.2$ (Van de Steene & van Hoof 2003). The excess emission in the R_c-band is due to the strong Hα emission. The terminal stellar wind velocity as determined from this P-Cygni type Hα emission is about 126 km s^{-1} (Van de Steene et al. 2000b). The SED clearly shows excess emission in the L- and M-bands as well, possibly indicating the presence of hot dust. The central star has spectral type B7 (Van de Steene et al. 2000b), indicating a temperature $T_{\rm eff}$ = 13,000 ± 1000 K and $\log(g/\mathrm{cm\,s^{-2}}) = 2$ (Van de Steene & van Hoof 2003; Reyniers 2003). The central star is not hot enough to significantly ionize the surrounding AGB shell. This is corroborated by the absence of typical planetary nebula lines in the optical and near-infrared spectrum of this object, and the fact that it has not been detected in the radio (Van de Steene et al. 2000a). The distance is about 2.2 ± 0.4 kpc, assuming a luminosity of 10,000 $L_\odot$ (Van de Steene & van Hoof 2003). This is in good agreement with the distance determination by Su et al. (2001) of 1.9 kpc assuming a luminosity of 6000 $L_\odot$.

Fig. 1 shows an HST picture of IRAS 16594−4656 through the F606W filter (Hrivnak et al. 1999). It has a multipolar reflection nebula inclined at intermediate orientation (Su et al. 2001), an elliptical halo of 12.3″x 8.8″, and arcs. Its CO expansion velocity is at least 16 km s^{-1} (Loup et al. 1990). The ISO spectrum showed that the nebula has a C-rich chemistry (García-Lario et al. 1999), although tentative indications for the presence of crystalline silicates were found.

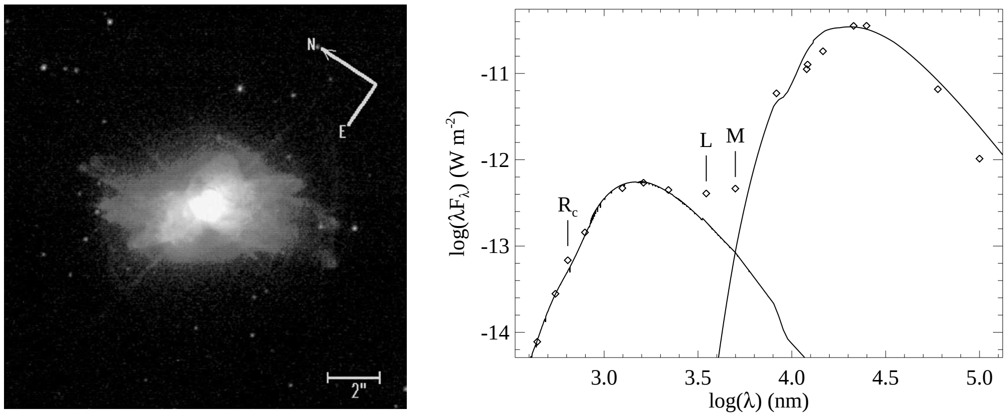

Figure 1. The HST image of IRAS 16594−4656 (Hrivnak et al. 1999) and its spectral energy distribution.

2. H_2 Emission

We obtained a full *JHK*-band near infrared spectrum of IRAS 16594−4656 with *SOFI* at the NTT (ESO). We detected numerous H_2 lines. The strongest H_2 emission is seen from (1,0) Q(1), (1,0) S(1), and (1,0) Q(3). The weakest line is (2,1) S(1), and no other lines with $v = 2$ or higher have been detected.

There are two likely excitation mechanisms for H_2 in post-AGB stars: UV pumping by stellar photons and thermal excitation. We analyzed the H_2 lines to derive the excitation mechanism. More details can be found in Van de Steene & van Hoof (2003). Fig. 2. provides a graphical summary of this analysis. Comparison of the population of upper levels with different rotational quantum numbers (J-values), but identical vibrational quantum numbers (v-values), provides an estimate for the rotational temperature: $T_{\rm r} = 1440 \pm 80$ K. The vibrational temperature is measured from the slope of a line passing through data points with different vibrational quantum numbers but the same rotational quantum number. This yields $T_{\rm vib} = 1820 \pm 240$ K. The fact that the two values differ only by 1.6 σ is consistent with the assumption that in H_2 is mainly collisionally excited. We also determined the ortho-to-para ratio of molecular hydrogen. This is the ratio of the total column density of ortho-H_2 (all odd J states) to para-H_2 (all even J states). We found a ratio of 2.77 $\pm$ 0.19, in good agreement with the expected ratio of 3 for collisionally excited molecular hydrogen. A simple model showed that it is unlikely that H_2 is thermally excited by UV heated gas. Hence H_2 must be shock excited in IRAS 16594−4656.

The ratio H_2 (1,0) S(1) to Brγ is 8.4 after correction for extinction. Molecular lines produced by collisional excitation of H_2 will be strongest if the collisions are not energetic enough to dissociate H_2 and lower its abundance (Hollenbach & McKee 1989). Such conditions exist in C-shocks because the gas is heated gradually and remains molecular. Therefore the strong H_2 emission in IRAS 16594−4656 argues in favor of a C-shock. C-shock models of Le Bourlot et al. (2002) indicate that H_2 is excited by shocks with a velocity of 30 km s^{-1} in material with a density of 10^3 cm^{-3}.

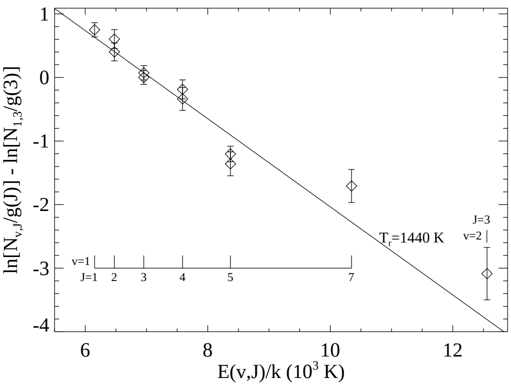

Figure 2. The column densities for the various observed rovibrational levels of H_2. The y-axis shows the log of the relative column density of molecular hydrogen in a given state, $N(v, J)$, divided by the statistical weight, $g(J)$. The best-fit line based on a rotational temperature of $T_\mathrm{r} =$ 1440 K is shown as well.

In order to investigate the velocity structure and extent of the H_2 emission in IRAS 16594−4656 we obtained spectra with *PHOENIX* on Gemini South at 3 position angles. The H_2 emission is spatially extended. The velocity difference between the peaks is 15 km s^{-1} (Fig. 3).

3. [Fe II] 1.644 μm Emission

The [Fe II] 1.644 μm line was also detected in the *SOFI* spectrum. The [Fe II] $a\,^4F$–$a\,^4D$ 1.644 μm over Brγ intensity ratio is often used as an indicator of shock excitation. The ratio expected for shock-excited gas is much larger than 1, but the [Fe II] 1.644 μm/Brγ ratio expected for radiatively excited gas is only approximately 0.06 (Graham et al. 1987). The ratio which we obtained for the dereddened lines is 0.9, which is much larger than the value typically found in H II regions. Hence the [Fe II] emission is possibly shock excited. However, because the ionization potential of neutral iron is 7.87 eV, and the dissociation energy of H_2 is 4.48 eV (Graham et al. 1987), in principle H_2 and Fe^+ cannot coexist in the same region in substantial quantities. Therefore the H_2 and [Fe II] emission must originate from different regions.

The *PHOENIX* spectrum shows that the [Fe II] emission is not extended. Hence [Fe II] must originate close to the central star, possibly in the post-AGB wind itself. Shock waves induced by stellar pulsations were proposed to explain the [Fe II] emission in Mira variables (Richter et al. 2003). Post-AGB stars are of course hotter than Miras, but they are usually variable and still pulsating. Fokin et al. (2001) argue that stellar pulsations are forming shocks in the atmosphere of the post-AGB star HD 56126. Miras are believed to have very high mass loss rates, but the mass loss rate in post-AGB stars may still be quite large as well (up to 10^{-5}-10^{-6} M$_\odot$ yr^{-1}, Gauba et al. 2003), as may be indicated by the strong P-Cygni Balmer lines in the optical spectrum of IRAS 16594−4656 (Van de Steene et al. 2000b). Moreover, post-AGB stars have higher wind velocities, which lead to the same normalized [Fe II] peak fluxes at lower pre-shock densities. Alternatively, shocked [Fe II] could occur where matter transferred from a binary companion hits an accretion disk. At this stage there is no corroborating evidence that either a binary companion or an accretion disk exists in IRAS 16594−4656, although the excess emission in the L- and M-bands would be consistent with such an interpretation.

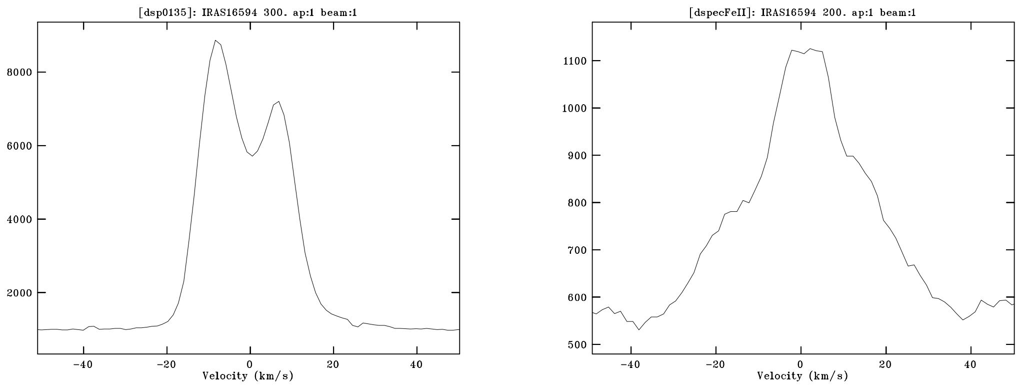

Figure 3. The H_2 and [Fe II] *PHOENIX* spectra at 7 deg PA.

4. Conclusions

IRAS 16594−4656 is a multipolar nebula of which the B-type central star is optically visible. Analysis of the near-infrared spectrum of this object shows the presence of shock excited emission, but no photo-ionization. This object gives us the unique opportunity to study wind-nebula interaction, yet uncompromised by ionization of the circumstellar shell.

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