Fast and furious: Modeling the cometary structure of the planetary nebula HFG1

Alexandros Chiotellis  
(National Observatory of Athens)

P. Boumis, N. Nanouris, J. Meaburn, G. Dimitriadis  
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Planetary Nebulae (PNe)

- Large expanding shells of ionized gas
- Their nature is connected with last stage of low/intermediate mass stars (~ 1-8 M☉)
- Formed by the mass outflows that accompany the death of the star and the formation of a white dwarf
Planetary Nebulae (PNe)

Interactive Stellar Wind theory (Kwok et al. 1978)

- AGB: slow dense stellar wind
Planetary Nebulae (PNe)

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Planetary Nebulae (PNe)

Interactive Stellar Wind theory (Kwok et al. 1978)

- AGB: slow dense stellar wind
- Contraction of AGB core: Fast tenuous wind
- Photoionization from the hot central star
Diversity of Planetary Nebulae

For non-spherical PNe more ingredients are needed to be introduced:

- Binary central star → Aspherical mass outflows
- Magnetic fields
- Inhomogeneous ambient medium
The intriguing case of HFG1

- 9 arcmin asymmetric nebula
- 15 arcmin bow-shaped outer shell (Heckathorn+ 1982)
- Long collimated tail: < 20 arcmin long; 5 arcmin wide (Boumis+ 2009)
- Proper motion: PM = 13 ± 1.5 mas yr\(^{-1}\)

“HFG1 morphology is due to the interaction of the local ambient medium with the supersonically PN” (Boumis+ 2009)
1. **The first observed PN which reveals a bow – shaped shell**
   - Geometry of a bow shock: function of $\frac{dM}{dt}$, $n_{\text{ISM}}$, $u_{\text{star}}$
   - Detection of optical bow shocks could be used for determine the properties of the stellar wind

2. **Central binary V664 Cas**: main sequence + luminous O- Type subdwarf (SdO)
   - SdO subdwarfs: remnant of a stellar evolution beyond the AGB phase?
   - If yes PNe associations are needed $\Rightarrow$ only few PNe + SdOs systems have been observed (Aller+ 2014)
Hydrodynamic Modeling of HFG1

Code: AMRVAC (Keppens et al. 2003)

- Continuous spherically symmetric inflow in the form of a stellar wind
- ISM is entering the grid antiparallel to the y-axis

Input parameters:
- \( \frac{dM}{dt} = 10^{-7} - 10^{-5} \, M_\odot \, \text{yr}^{-1} \)
- \( u_w = 5 - 15 \, \text{km s}^{-1} \)
- \( u_{\text{star}} \rightarrow \text{PM} = 13 \pm 1.5 \, \text{mas yr}^{-1} \)
- \( n_{\text{ISM}} \rightarrow P_{\text{wind}} = P_{\text{ISM}} \)
Results

Models with time invariant wind and ISM properties:

- Reproduces the stagnation point radius ✓
- More extended shell ✗
- The tail starts far away from the central star ✗
- Reproduces the width and length of the tail ✓
- Smaller stagnation point radius ✗
- The overall structure of the shell is much smaller ✗
Models with time invariable stellar wind/ISM properties cannot reproduce HFG1.

**Time variability?**

- $t_1: P_{\text{wind}} = P_{\text{ISM}}$
- $t_2: P_{\text{wind}} \uparrow \text{or and } P_{\text{ISM}} \downarrow$

**What is changing with time?**

- The ISM medium decreased
- The systemic velocity decreased
- The mass loss rate increased

A "coincidence" is needed

**Motivation: stellar evolution**

AGB winds are time variable!
HFG1 based on the properties of V664 Cas

Stellar evolution models: Progenitor of the $0.57 M_\odot$ sdO was a $3 M_\odot$ AGB star

![Graph showing logarithm of mass loss rate against TP-AGB timescale](image1.png)

3 $M_\odot$ AGB
(Nanni+ 2013)

![Graph showing radius against time](image2.png)
Results

- Introduce fast wind based on the post-AGB evolution models
- Photoionization: $T \rightarrow 10^4$ K for regions with gold plasma ($T < 1000$ K)
Conclusions

- The cometary structure of HFG1 results from the supersonic motion of the PN in respect to the local ISM.
- The morphological properties of HFG1 can be explained by the AGB and post-AGB evolution models for a $3 \, M_\odot$ star.
- This result is aligned with the current observed properties of SdO primary of V664 Cas.
  - bridges the PN properties with the evolution of its central star.

What has been shown from HFG1 modeling:

- AGB winds *must* be variable to explain its morphology.
- Verifies the predictions AGB and post-AGB evolution theory towards the formation of sdO stars.
Alternatives

- Models with time invariable stellar wind ISM properties cannot reproduce HFG1

Time variability?

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A "coincidence" is needed

\[ P_{\text{ISM}} = n_{\text{ISM}} \times u^2_{\text{star}} \]
\[ P_{\text{wind}} = \frac{(dM/dt) \times u_{\text{wind}}}{(4 \pi r^2)} \]

Motivation: stellar evolution

AGB winds are time variable!
A model for HFG1

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- \(u_w = 5 - 15 \text{ km s}^{-1}\)
- \(u_{\text{star}} \rightarrow \text{PM} = 13 \pm 1.5 \text{ mas yr}^{-1}\) (observed)
- \(n_{\text{ISM}} \rightarrow \text{stagnation point}:\)
  \[P_{\text{wind}} = P_{\text{ISM}} \Rightarrow n_{\text{ISM}} = 1.78 \times 10^{3} \frac{(dM/dt \cdot u_w)}{(R_s \cdot u_{\text{star}})}\]
A model for HFG1

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**Distance dependent:**

\( D_{\text{HFG1}} = 310 - 950 \text{ pc} \) (Exter+ 2005)

→ Large uncertainties are introduced to the model
Re-estimation of HFG1 distance

- Model the spectral energy distribution of the secondary star of V664 Cas (following Bonanos 2006):

\[
\frac{f_\lambda}{F_\lambda} = \frac{1}{D^2} \cdot R^2 \cdot 10^{-0.4A(\lambda)}
\]

Re-estimated distance: \( D_{HFG1} = 480 \pm 40 \text{ pc} \)