HR4049: signature of nova nucleosynthesis?

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The post-Asymptotic Giant Branch (AGB) star HR4049 is in an eccentric binary system with a relatively short period probably surrounded by a dusty circumbinary disk. Extremely anomalous oxygen isotopic ratios, $^{16}\text{O}/^{17}\text{O} \approx ^{16}\text{O}/^{18}\text{O} \approx 7$, have been measured from CO$_2$ molecules likely residing in the disk. Such a composition cannot be explained in the framework of AGB and post-AGB evolution while it can be qualitatively associated with the nucleosynthesis occurring during nova outbursts. We discuss nova models, the presence of a white dwarf companion to HR4049 and possible scenarios for the dynamical evolution of this binary system. Circumbinary disks in which mixing occurs between red-giant and nova material may also be invoked as the site of formation of some rare types of meteoritic presolar grains.

1. Introduction

HR4049 is a post-AGB star member of a binary system with period of 429 days and high eccentricity, $\epsilon=0.3$. HR4049 is the prototype of a group of post-AGB stars in binary systems showing a high degree of metal depletion, $< -4$ dex \cite{1}. The key to this feature is probably the presence of a massive, stable, long-lived and dusty circumbinary disk: after dust forms in the disk the gas depleted of refractory elements is re-accreted by the star, see e.g. \cite{2}. Oxygen isotopic ratios have been measured from CO$_2$ molecules likely residing in the disk \cite{3}. These ratios are extremely anomalous: $^{16}\text{O}/^{17}\text{O} = 8.3 \pm 2.3$ and $^{16}\text{O}/^{18}\text{O} = 6.9 \pm 0.9$, as illustrated in Figure\textsuperscript{1} they are one to more than two orders of magnitude lower than observed in any evolved star! Such a composition cannot be produced in AGB and post-AGB stars because their composition is characterised by the effect of He burning, during which $^{17}\text{O}$ and $^{18}\text{O}$ are destroyed, and proton-capture processes during which $^{17}\text{O}$ is produced, but not to the level shown by HR4049, and $^{18}\text{O}$ is destroyed.
Figure 1. Oxygen isotopic ratios in HR4049 are compared to those of other evolved stars.

Figure 2. C and N isotopic ratios in mainstream, A+B and nova SiC grains. Lines indicates mixing of solar with nova material from models by [9]. Numbers along the lines indicates the mass fraction of solar material in the mix.

2. Nova nucleosynthesis?

If the companion of HR4049 is a white dwarf (WD), accretion from HR4049 could have triggered nova outbursts in the same way as predicted [4] and observed [5] in some symbiotic systems. The nova ejecta could have been partly intercepted by HR4049 or the circumbinary disk, to produce the observed anomalous oxygen ratios. The mass of HR4049 is between 0.56 – 0.67 $M_\odot$ and the mass function of the system is $f(m)=0.158 \pm 0.004$. The estimated inclination is $\sim 60$ degrees [2]. Hence the mass of the companion can be estimated to be around 0.75 – 0.82 $M_\odot$, which indicates we should look into nova models with a CO white dwarf. Oxygen isotopic ratios for CO nova models are shown in Table 1. Results depend on several parameters: the mass, temperature and luminosity of the WD, the accretion rate, the composition of the envelope produced by the accreted material and the level of mixing of WD material into this envelope. In order to be able to match the observed ratio $^{16}\text{O}/^{17}\text{O} \leq 8$ is needed. Nova models appear to allow such composition, depending on the choice of parameters. Note also that variations of the $^{16}\text{O}(p, \gamma)$, $^{17}\text{O}(p, \gamma)$ and $^{17}\text{O}(p, \alpha)$ reaction rates within their uncertainties give rise to $^{17}\text{O}$ abundances changes by factor $\leq 30$ [10].

Isotopic ratios of $^{16}\text{O}/^{18}\text{O}$ presented by Ref. [2] for CO nova models are also shown in Table 1. These nova models do not produce the observed ratio, requiring $^{16}\text{O}/^{18}\text{O} \leq 7$. However, the final abundance of $^{18}\text{O}$ originates predominantly from the decay of
Table 1
Ranges of oxygen isotopic ratios from nova models

| Reference | $M_{WD} (M_{\odot})$ | $^{16}\text{O}/^{17}\text{O}$ | Varied parameters                  |
|-----------|---------------------|------------------|-----------------------------------|
| 6         | 1.                  | 2.6 — 21         | Luminosity and $^{12}\text{C}$    |
| 7         | 1.                  | 0.52 — 120       | Envelope mass and composition     |
| 8         | 0.65                | 19 — 52          | WD temperature and the accretion rate |
|           | 1.                  | 3.1 — 17         |                                   |
| 9         | 0.8                 | 39 — 57          | Level of mixing with core material |
|           | 1.                  | 30               |                                   |
| 11        | 0.8                 | 155 — 446        | Level of mixing with core material |

$^{18}\text{F}$, whose abundance is very sensitive to $^{18}\text{F}(p, \alpha)$, $^{17}\text{O}(p, \gamma)$ and $^{17}\text{O}(p, \alpha)$ reaction-rate variations. Within rates uncertainties, the $^{18}\text{F}$ abundance changes by factors of $\leq 100$. Thus, within current uncertainties also the required $^{16}\text{O}/^{18}\text{O}$ ratio could be produced by CO nova models.

The main question in relation to the nova scenario is whether the companion of HR4049 is really a WD. There is no sign of the presence of a WD in the ultraviolet spectrum so that, if there is one, its temperature must be lower than $\sim 20,000$ K. If the WD is still accreting from HR4049 winds it could emit X-rays. ROSAT observations suggest that there might be a marginal detection about 20" away from HR4049 position, on the edge of being compatible with the positional accuracy of ROSAT (F. Verbunt, personal communication). A more sensitive observational test can be obtained making use of the higher resolution of CHANDRA.

Many other issues are open with regards to the evolution of the system. With a separation of 190 $R_{\odot}$, the Roche-lobe radius is $\sim 76 R_{\odot}$. The radius of HR4049 at the tip of the AGB would have been $\sim 250 R_{\odot}$, much larger than the Roche-lobe radius. Several scenarios can be proposed for the evolution of this binary system. For example, if the system initially had a larger separation nova outbursts could have been triggered by wind accretion before dynamically unstable Roche-lobe overflow resulted in common envelope evolution and orbital shrinkage. Alternately, if the mass ratio reached a value smaller than about 2/3 the system could have undergone stable Roche-lobe overflow for some time and triggered nova outbursts. However, in either case it is difficult to account for the current high eccentricity of the binary system.

3. Relevance to meteoritic presolar grains

The compositions of a few presolar SiC and graphite grains indicate a nova origin. There a few open problems and questions related to this origin: (i) mixing between nova and more normal material is needed, (ii) C/O $> 1$ is not typically produced by novae,
but is a necessary condition to condensate SiC and graphite, and (iii) grain compositions indicate an ONe nova origin, but where are the grains from CO novae?

If we consider as a site of grain formation the circumbinary disks around evolved stars, such as that around HR4049, we can find solutions to the three problems listed above. (i) In a circumbinary disk nova material could be mixed with red giant material. (ii) Material from the red giant stars could be carbon rich and, finally, as illustrated in Figure 2 (iii) grains originating from material affected by CO nova nucleosynthesis could be found among grains belonging to the A and B SiC populations, whose composition has so far remained unexplained [13]. An objection to this scenario is that there are few circumbinary disks around evolved stars and not all of them could have experienced nova nucleosynthesis. How can they produce a significant fraction (few percent) of the recovered meteoritic presolar SiC grains? A possible explanation is that many presolar meteoritic SiC grains, which have relatively large sizes up to a few $\mu$m, could have been preferentially produced in circumbinary disks, rather than in single-star outflows [14].

4. Summary and conclusions

The O composition of HR4049 could represent the first time that isotopic ratios showing the signature of nova nucleosynthesis are measured in a stellar environment. This composition could have resulted from nova outbursts if: (i) the companion of HR4049 is a WD and (ii) the $^{18}$F($p, \alpha$) rate is close to its lower limit, so that $^{18}$O can be produced to the same level as $^{17}$O. Dedicated nova models are needed to address the issue. Many problems related to the system dynamics are still open. A significant fraction of presolar SiC grains could have originated in circumbinary disks with material being affected by nova nucleosynthesis.

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