Hubble Space Telescope

Cycle 15 GO Proposal

Can mass-ejections from late He-shell flash stars constrain convective/reactive flow modeling of stellar interiors?

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Instruments: ACS

Proprietary Period: 12

Orbit Request	Prime	Parallel
Cycle 15	5	0

Abstract

The existence of H-deficient knots around the central stars of the planetary nebulae Abell 30 and Abell 78 is still unexplained. We hypothesize that these knots were ejected during a very late helium-shell flash (= very late thermal pulse, VLTP) suffered by the precursor white dwarf stars. If this is true, then the characteristics of these knots (mass, velocity, density, spatial distribution) allow to draw conclusions on the course of the hydrogen-ingestion flash detonation that is triggered by the He-shell flash. This provides important, otherwise inaccessible constraints for the hydrodynamical modeling of convective/reactive flows in stellar interiors. Understanding the physics of these flows is not only important for the understanding of these particular central stars, but also for the frequent, very similar convective/reactive events that determine the nucleosynthesis in Pop. III stars.

With this proposal we want to proof or discard the idea that the H-deficient knots are resulting from a VLTP. If true, then they can be exploited for flash-physics diagnostics. We propose a simple test. We search for such knots around five H-deficient central stars (PG1159 stars). Our models predict, that only those stars with residual nitrogen in the atmosphere have suffered a VLTP and, hence, should have expelled knots. We therefore want to take [O III] images of stars which have photospheric N and those which do not.

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Number of investigators: 5

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Target Summary:

Target	RA	Dec	Magnitude
LONGMORE-4	10 05 45.7800	-44 21 33.30	V = 16.6
NGC-246	00 47 3.3400	-11 52 18.92	V = 11.95
K1-16	18 21 52.2100	+64 21 54.30	V = 15.4
RXJ2117.1+3412	21 17 8.2900	+34 12 27.20	V = 13.2
PG1144+005	11 46 35.2300	+00 12 33.60	V = 16.2

Observing Summary:

Target	Config Mode and Spectral Elements	Flags	Orbits
LONGMORE-4	ACS/HRC Imaging F502N		1
NGC-246	ACS/HRC Imaging F502N		1
K1-16	ACS/HRC Imaging F502N		1
RXJ2117.1+3412	ACS/HRC Imaging F502N		1
PG1144+005	ACS/HRC Imaging F502N		1

Total prime orbits: 5

Scientific Justification

Scientific Background The final phase of evolution of low- and intermediate-mass stars begins with their departure from the AGB. They evolve at constant luminosity to extremely high $T_{\rm eff}$ ($>$100 kK) while burning H or He in shells. When nuclear burning ceases, the stars begin to fade and cool and enter the hot end of the white dwarf (WD) cooling sequence. Standard post-AGB (pAGB) evolution theory predicts that the chemical surface composition of the star remains H-rich, because shell burning stops when the H-rich surface layer and the He-rich intershell region have been thinned down to a certain extent. The metal content in the H-rich stellar mantle is only slightly altered by the 3rd dredge-up, which brings nuclear processed matter to the stellar surface. This metal-enriched matter is fed into the ISM by mass-loss from the AGB star. Understanding the mixing and burning processes that determine the metal yields of AGB stars is essential for our picture of galacto-chemical and early-universe evolution. But there are a number of uncertainties (convective overshoot, nuclear cross-sections) which enter the evolution models and which can strongly affect the predicted yields. Observational constraints on these uncertainties are required.

This scenario is valid for the majority of pAGB stars, however, there is a considerable fraction of stars which obviously does not fit into this standard picture. About 25% of the pAGB stars in the PN and immediate pre-WD stage are H-deficient. The particular interest in these extraordinary stars originates from their potential to put strong observational constraints on the uncertainties in AGB evolution models and, hence, ISM enrichment. From spectroscopic analyses (see review by Werner & Herwig 2006) the following picture emerged. The Wolf-Rayet type central stars (spectral type [WC]) are on the horizontal part of evolutionary tracks leading away from the AGB, with a mean luminosity of log $L/{\rm L}_\odot$=4. They span a broad temperature range ($T_{\rm eff}$=20–140 kK). When they become hot enough and their mass-loss rate drops below $\dot{M}=10^{-8}{\rm M}_\odot$/yr, the [WC] stars evolve into PG1159 stars. These are immediate WD progenitors and start out to evolve from high $T_{\rm eff}$ (200 kK) and high luminosity (log $L/{\rm L}_\odot$=4) and finally turn into He-rich (non-DA) WDs at about $T_{\rm eff}$=70 kK and log $L/{\rm L}_\odot$=1.

[WC] and PG1159 atmospheres are mainly composed of He, C, and O (about He=40%, C=50%, O=10%, by mass). These peculiar abundances suggest that the origin of the H-poor pAGB sequence is a late He-shell flash (Iben et al. 1983). Under certain circumstances a pAGB star can re-ignite He-shell burning. This can occur in early pAGB phases or later, when the star has already become a WD. The star returns onto the AGB ("born-again AGB star") and retraces the pAGB evolution for a 2nd time. The flash causes a complete mixing of the H-rich stellar mantle ($10^{-4}\,{\rm M}_\odot$) with the entire He/C/O-rich intershell region ($10^{-2}\,{\rm M}_\odot$), so that eventually the surface abundances reflect the intershell abundances which have been built up during the previous thermally-pulsing AGB-phase. The intershell comprises He (H-burning ashes) and C/O (He-burning ashes) that was dredged up from the stellar core. In addition, the exposed material contains species that were affected by n-captures during the AGB phase in the s-processing region within the intershell. Well-known examples for "born-again" stars that have suffered a late He-shell flash in historical time are FG Sge and Sakurai's object. The spectroscopic abundance determination of elements in the atmospheres of born-again pAGB stars directly reveals details of interior mixing and burning processes which are usually not accessible. The comparison of observed abundances with model predictions is a strong constraint for evolutionary models.

The course of a late He-shell flash and the resulting surface abundances essentially depend on the moment *when* it occurs. There are two scenarios (Herwig et al. 1999). A **late** thermal pulse (LTP) is a He-shell flash that occurs during the post-AGB phase when the star still has a H-burning shell (i.e. on the horizontal part of the track in the HRD, before the "knee"). As a consequence, the H-rich mantle is mixed with the He-rich intershell matter. Thus, H is *diluted* to the extent that it becomes spectroscopically undetectable ($< 1\%$). A **very late** thermal pulse (VLTP) is a flash that occurs when the star is already on the WD cooling track. H is ingested and *burned* completely.

The modeling of a VLTP is particularly challenging because of the violent convective/reactive processes. H, mixed downward by the He-shell ignition, begins to burn as soon as it reaches depths hot enough. It occurs a so-called Hydrogen-Ingestion Flash (HIF, Herwig et al. 2006). Up to now this complex process is simulated only with parametrized, quasi-static 1D models, but it seems clear that hydrodynamical simulations will give different results concerning the course of burning and mixing of material. We have recently begun 3D hydro-simulations for convective/reactive flows relevant for evolutionary calculations of a VLTP. Since such simulations in the context of pAGB-evolution are the very first steps to describe the physics in a more realistic manner, we are seeking for observational benchmarks. One such benchmark is the observed surface abundance pattern of H-deficient pAGB stars mentioned above. Another complementary benchmark, which is the topic of this proposal, is the influence of a He-shell flash on the circumstellar environment. It is based on the discovery of H-deficient nebular knots in the close vicinity of two H-deficient central stars, Abell 30 and Abell 78 (e.g. Borkowski et al. 1993), being [WC]/PG1159 transition-type objects. The knots recede from the stars with ≈200 km/s, which is much higher than the escape velocity from an AGB star (≈20 km/s), but much lower than the escape velocity from the compact central stars (≈4000 km/s, that is roughly the terminal velocity of their radiatively driven winds). The knots are located in the innermost parts of the (otherwise H-rich) PN (Fig. 1). It is unclear how the clumps of H-deficient material have left the star.

We hypothesize that the H-deficient knots were expelled immediately after the onset of the VLTP. Our hydro models show that material can exceed the escape velocity while the star is on its way back from the WD to the AGB stage. This can explain the intermediate velocity of the knots. The local confinement of the high convective velocities can explain the non-spherical clumpy mass-loss. Fig. 2 is a snapshot of our simulations. We see a blob rising with ≈10 000 km/s and forming a shock at the leading edge. The corresponding energy generation clearly shows that we see a detonation here. We are not be too concerned about the fact that 10 000 km/s is much more than what is observed for the blob velocities in Abell 30/78. As explained with Fig. 2, our models are still immature, and the only thing they motivate is that H-deficient blobs shooting out from the He-shell flash convection during a HIF seems possible.

There is a clear observational possibility to test this idea. Excessively large convective velocities occur only in the VLTP case and *not* in the LTP case. So we should *not* see H-deficient knots around objects which have suffered an LTP (which goes without an HIF). How can we know if a PG1159 star has suffered an LTP or a VLTP? There is a marker that clearly allows to decide. In the VLTP case, H is *burned* and transformed into N. The models predict a strongly enhanced N surface abundance, of the order 1%, which is readily detectable in optical/UV spectra (e.g. Werner & Herwig 2006). In contrast, in the LTP case (H-envelope and He-rich intershell get mixed, no

H-burning occurs), almost no N is expected to survive: The roughly solar N-abundance in the H-envelope gets diluted when mixed with the massive He-rich intershell that is free of N (N was destroyed by α-captures and transformed into neon). In essence, *the detection or non-detection of N in a PG1159 star means that the object suffered a VLTP or LTP, respectively.*

What about N in Abell 30 and 78? We found an abundance of about 1% (Werner & Koesterke 1992). They clearly suffered a VLTP, consistent with our idea that the VLTP caused the H-deficient knots. The time elapsed between commencing of the VLTP and the star's evolution towards its current position in the HRD ($\approx$1000 yrs when compared to our evolution models) is in agreement with the dynamical age of the knots. This calls for a search of H-deficient knots around other PG1159 stars. *If we find such knots* only *at N-rich objects, then our hypothesis is confirmed. But if we find such knots also around an N-deficient PG1159-star, then our hypothesis is wrong: The matter cannot have been expelled as a direct consequence of a VLTP.* If the VLTP is indeed responsible for the excessive acceleration of matter, then we have in principle a means to derive conclusions about the convective/reactive flows by determining the characteristics of the knots (mass, density, velocity, spatial distribution).
It is our immediate aim to search for Abell 30 /78-like knots around PG1159 stars. We selected VLTP and LTP objects, i.e. N-enriched and N-depleted stars. The results uniquely allow to confirm or discard the idea whether the H-deficient knots are expelled exclusively from VLTP stars. The most sensitive search tool is O III imaging in the forbidden 5007 Å emission line, because we expect it to be the brightest one (Borkowski et al. 1995). The Abell 30 observation with HST/WFPC2 as compared to ground-based observations in that paper clearly shows that the close vicinity of the knots to the central star calls for highest possible angular resolution. This can only be achieved with HST. We choose the ACS/HRC with F502N, which is 3 times more sensitive than WFPC2/PC. We selected targets with stellar parameters similar to Abell 30/78, i.e. their age since the He-shell flash is of the same order. For younger objects ([WC]s), the knots might be too close to the central star to be resolved. At older objects the knots may be have been dissolved by the ablating interaction with the fast stellar wind. There are 5 objects which fulfill these criteria (Tab. 1).

Significance to Astronomy The proposed observations will determine whether H-deficient knots around PG1159 stars are the result of H-flash detonations in the framework of the VLTP. If this is indeed the case, we will be able to use the observable properties of these knots as a powerful tool to constrain an entirely new, emerging class of hydrodynamic simulations of convective/reactive events. While the born-again stars may be our best chance to study the physics involved, the reactive/convective events encountered here are frequently found in stellar evolution models of Pop. III stars or ultra- metal poor stars that were born in the nascent Universe (e.g., Iwamoto et al. 2004). Ultimately, the proposed observations may prove a key ingredient to construct a predictive mode for nucleosynthesis in the first generations of stars.

Some PG1159 stars are pulsators, defining the GW Vir instability strip in the HRD. The asteroseismology-derived interior stratification is in qualitative agreement with our evolutionary models, however, a significant problem remains: The existence of non-pulsators in the strip. It is interesting in the context of this proposal, that the non-pulsators are N-deficient, i.e., they have suffered a LTP, not a VLTP. It is our hope that our hydro-models will be able explain this dichotomy.

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Iwamoto, N., Kajino, T., Mathews, G. J., Fujimoto, M., & Aoki, W. 2004, ApJ, 602, 377
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Description of the Observations

We propose to image the close vicinity of five targets with the ACS/HRC through the [O III] filter F502N to search for faint nebular knots. A rigid estimation of the required exposure times is not straightforward. As a coarse guideline, we use the WFPC2/PC1 image (Fig. 1) of Abell 30, which allows a detailed analysis of the knots' morphology. The brightest parts of the largest knots have 20 cts/pixel after 3600 sec of integration time. One count/pixel corresponds to a surface brightness of 6.6×10^{-15} erg/cm^2/sec/arcsec^2, i.e., the surface brightness of the brightest knot regions is 1.3×10^{-13} erg/cm^2/sec/arcsec^2. We want to observe each target for one orbit, i.e., about 40 minutes (1 orbit minus overheads). The shorter exposure time compared to the Abell 30 WFPC image is more than compensated by the factor of 3 higher efficiency of the ACS/HRC with the F502N filter. We assume that the surface brightness of possible knots around our targets is similar to Abell 30. Tab. 1 displays the spectroscopically determined distance to our targets and, for comparison, the distance to Abell 30. Our targets' distances are similar to that of Abell 30, within a factor of 2-3. We thus think it is a reasonable choice to spend one orbit for each target.

For the two brightest targets we need to split the exposure into several images in order to avoid overexposure of the central star and CCD blooming. For completeness, we note that PG1144+005 has no associated PN. This is not of concern here. This only means that the PN has already dispersed, because the VLTP hit the precursor WD very late on the cooling track. Fittingly, the object is N-rich, i.e., concerning to our models it must indeed be a VLTP-star.

Special Requirements

Coordinated Observations

Justify Duplications

4 of our 5 targets were imaged previously. The data are not useful for our purpose because:

Longmore 4: A very short (140 sec) WFPC2/PC1 image was taken with a broadband filter (F555W) for a snapshot proposal aiming at the search for cool companions around central stars. No nebulosity is detectable in this image. Note that this target is our most distant one.

NGC 246: Four 1000 sec images are in the archive, taken with WFPC2/WF2. However, these were taken with the Hα narrowband filter so that H-deficient knots cannot be detected.

K1-16: A short (350 sec) WFPC image exists, taken with a red wide-band filter (F785LP). No strong emission line is expected in the passband. No nebulosity is seen in the image.

RXJ2117.1+3412: Again, for a snapshot search for companions two very short images (18 sec and 66 sec) were taken in two different broadband filters. No nebulosity can be detected.

Table 1: Parameters of the five target stars. $T_{\rm eff}$, $\log g$, and information on presence of N are taken from Werner & Herwig (2006). The distances were derived spectroscopically comparing V flux and model-atmosphere flux. As a comparison, in the last line we list the respective values for Abell 30.

Object	$T_{\rm eff}$/K	$\log g$ (cgs)	V mag	distance/kpc	N present?
Longmore 4	120 000	5.5	16.6	6.4	no
NGC 246	150 000	5.7	11.95	1.1	no
K1-16	140 000	6.4	15.4	2.0	yes
RXJ2117+3412	170 000	6.0	13.2	1.4	no
PG1144+005	150 000	6.5	16.2	2.8	yes
Abell 30	110 000	5.5	14.3	3.5	yes

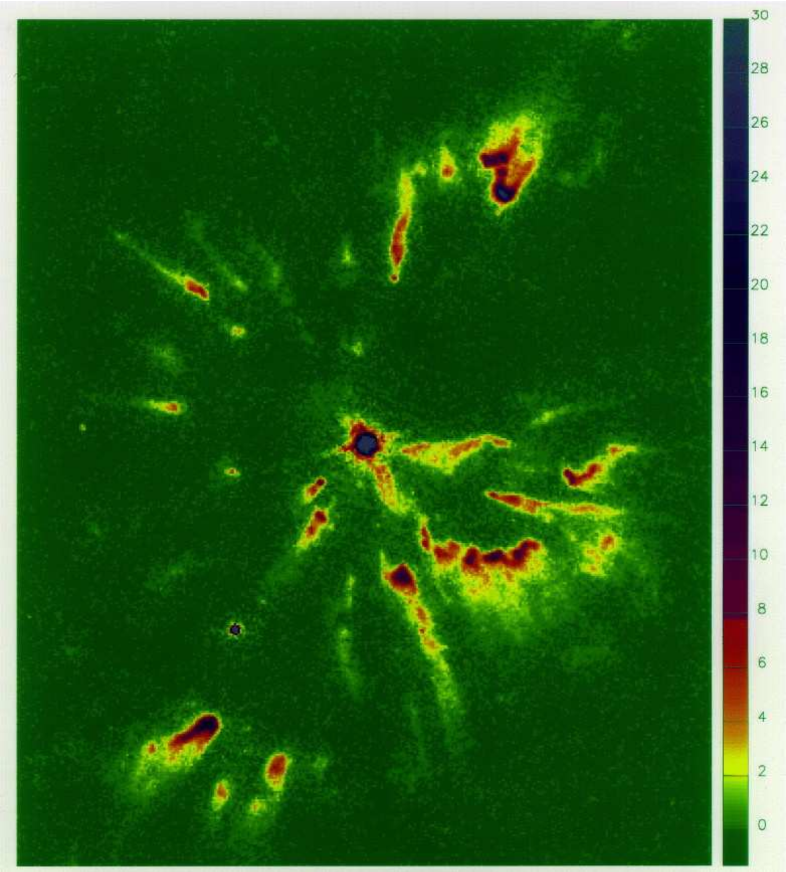

Figure 1: [O III] WFPC2 image of the H-deficient knots in the close vicinity of the central star of Abell 30 (from Borkowski et al. 1995). The field-of-view is 15.2” × 18.5”. The scale is counts/pixel. The clumpy material was ejected by the star about 1000 years ago. The knots have a cometary shape formed by the rapidly passing central star wind.

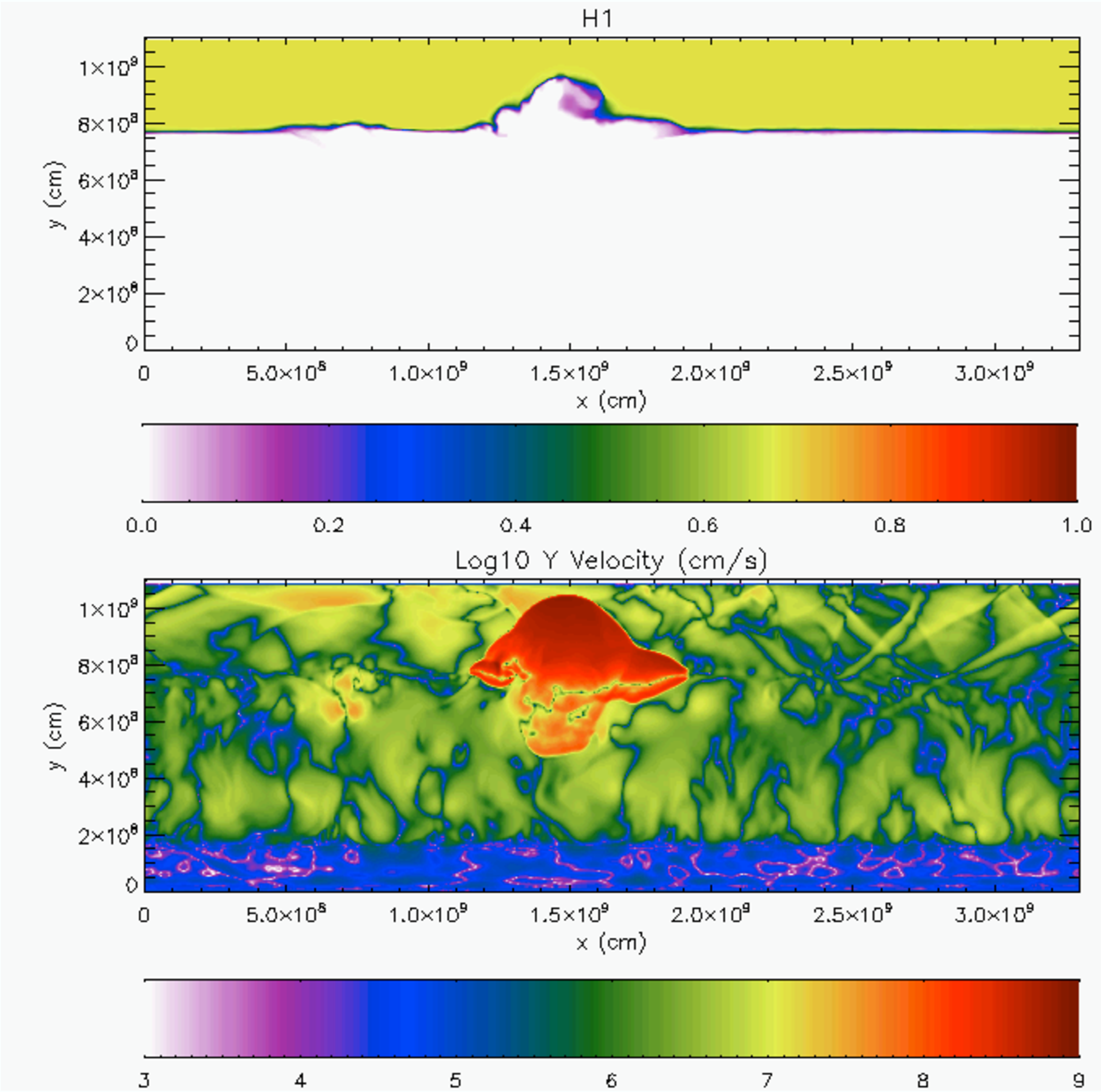

Figure 2: Snapshot from a hydrodynamical simulation of a hydrogen-ingestion flash triggered by a late He-shell flash. **Top panel:** A H-free blob starts to rise driven by the rapid energy release from burning due to H ingestion (displayed is the chemical stratification). The lower boundary of the H-rich zone is the upper boundary of the He-shell flash convection. The lower boundary of the He-shell flash convection can be seen in the **lower panel** that shows the vertical velocity. The marked jump in the lower half of the box represents the bottom of the He-shell flash convection zone. The velocity plot clearly shows a blob with about 10 000 km/s rising to the top, and forming a shock at the leading edge. At this point we have to classify the present simulation as a toy model because there are many things that are not realistic enough, including some scaling of energy generation rates, as well as details about the flame treatment, turbulent mixing, the setup itself, 2D and boundary effects. Nevertheless, all of these simplifications are not so major as to not take this preliminary result as a clear hint that H-deficient blobs around H-deficient post-VLTP stars (= PG1159 stars) can have their origin in these convective burning events that define the VLTP.