SOFIA and HST Multi-wavelength study of the Symbiotic Mira HM Sge

Time and Orbit Request:
SOFIA: FORCAST (1 hour), EXES (3 hours)
HST: WFC3 (2 orbits), COS (2 orbits)

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Abstract

To showcase the capabilities of evolved-star science using the instrument modes of SOFIA and the *Hubble Space Telescope* (HST), we propose to use FORCAST and EXES aboard SOFIA, and WFC3 and COS aboard HST to probe the quickly-evolving symbiotic system HM Sge. We will use SOFIA to probe the dust and the kinematics of the dense circum-stellar material, and HST to map the gas in the inner nebula and probe the shocked emission. These observations will provide a public dataset that can be used to anchor future observations of HM Sge, a post-outburst symbiotic Mira that displays a wide and diverse range of active astrophysical phenomena. The observations will also demonstrate the possibilities for future observations of other evolved-star systems.

Community Engagement

Our aim is to involve the evolved-star community as broadly as possible. To this end, we will advertise the program, and the availability of calibrated datasets in the monthly AGB newsletter. We will also prepare presentations at suitable sessions during the next AAS meeting. At STScI, there are several forums (such as "Science Coffee", and the "Low Density Universe (LDU) Lunch") where the project can be advertised widely. In the current situation, where remote talks are the norm, gathering an audience of interested researchers from across the globe is more easily achieved. We will also organize more formal events, with focused presentations appealing to graduate students, post-doctoral fellows, and their supervisors and mentors.

Introduction and Background

The Asymptotic Giant Branch Phase: As stars evolve and expend their nuclear fuel, they expand, cool, and begin to shed their outer layers. Evolved stars lose a tremendous amount of their material (up to 80%) in a relatively short amount of time (van Loon et al., 2005). This chemically-enriched material is used to seed the creation of new planets and stars, and was necessary for the creation of life itself. The Asymptotic Giant Branch (AGB) phase is the short-lived stage of evolution where small-to-intermediate mass stars lose most of their mass. These stars may be the largest contributors of dust in the Universe, and are critical for understanding the chemistry throughout galaxies.

As AGB stars lose mass, cool material leaving the star condenses and blankets the star in a layer of oxygen- or carbon-rich dust, depending on their mass and the available metals.

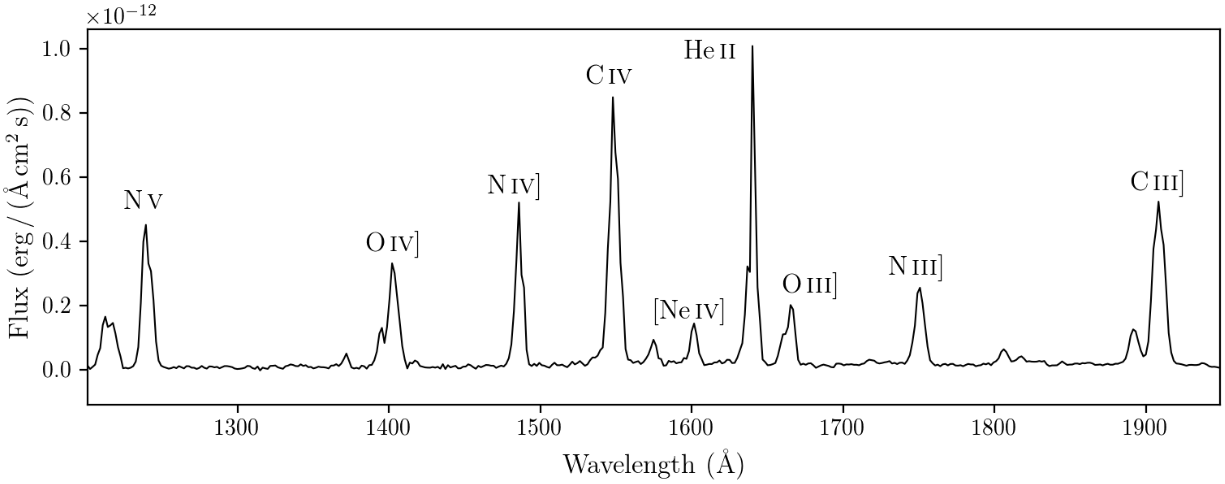

Figure 1 The IUE spectrum of HM Sge from Murset & Nussbaumer (1994). We will re-observed these lines to study how the shocks have evolved over the past 28 years.

This obscures the stars at optical wavelengths, but the light is absorbed by the dust and re-radiated in the infrared (IR). Our understanding of AGB stars and their effect on their surroundings depends critically on the ability to obtain IR data.

Multiple-star systems: It is expected that around one third of AGB stars are a part of a binary or multiple system. Around one third of the AGB stars from the DEATHSTAR project have also shown strong asymmetries in their CO envelopes (Ramstedt et al., 2020). High-resolution studies with the VLTI and ALMA have resolved the complex structure of the most nearby binary systems (Decin et al., 2019), and we are beginning to understand how companions affect AGB mass loss and their chemical enrichment of the local environment (see reviews by Höfner & Freytag, 2019; De Marco & Izzard, 2017).

Symbiotic Miras: Amongst the binary AGB systems are the fascinating Symbiotic Miras, where the cool donor star is a Mira variable exhibiting regular, large amplitude variability with a period of the order of a few hundred days, and the accreting companion is a hot subdwarf/post-AGB star or a hot White Dwarf (WD). The radiation from the hot companion, and the energy from jet-like outflows create a compact photo- and shock-ionized region around the central stars. Several Symbiotic Miras have undergone nova-like eruptions in their history, which has led to spectacular larger-scale nebulae such as the Southern Crab Nebula surrounding Hen 2-104. These systems will typically evolve into Planetary Nebulae, but in cases where the AGB star has a mass of about 5 $M_\odot$ or greater they may explode as single-degenerate Type Ia supernovae (e.g. Williams et al., 2012).

HM Sge, the Target of Interest: The Symbiotic Mira, HM Sge, drew much attention after its nova-like outburst in 1975 (Dokuchaeva, 1976), brightening six orders of magnitude in the optical. Unlike classical novae, the outburst remains near its peak brightness far longer than the expected few days (Ciatti et al., 1979). It is expected that the outburst was from a hydrogen flash from the WD companion (Stauffer, 1984). The system is composed of a cool and dusty oxygen-rich (M-type) AGB star accreting material onto a WD 60 au away (Eyres et al., 2001). The AGB star has a pulsation period of 527 days (Munari & Whitelock, 1989; Mürset & Schmid, 1999), an M7 spectral type, and is heavily reddened in the near-IR ($J - K \sim 3$ mag). These are all indicative of dust production, high mass loss, and a late stage of AGB evolution.

The post-outburst system was closely followed at visual wavelengths and, fortunately, also in the ultraviolet with IUE (Fig. 1). A series of observations obtained between 1978 and 1989 show that several lines such as He II 1640, C IV 1550, and N V 1240 increased rapidly in brightness up to 1985, and then remained steady, while the lower ionization lines (such as N III] 1750 and O III] 1664) started declining circa 1982. In contrast a few high ionization lines such as [Ne V] 1575, which are likely due to shocked gas, emerged only in 1985 (Mueller & Nussbaumer, 1985; Nussbaumer & Vogel, 1990).

High-resolution optical spectra obtained in 1983 revealed a bipolar mass flow with velocities up to 200 km/s and with slower moving features consistent with individual blobs or a rotating ring (Solf, 1984). The material from the bipolar outflow was resolved in HST/FOC optical images and also showed the presence of a slightly extended halo photoionized by the radiation from the hot component (Hack & Paresce, 1993). HST/WFPC2 images obtained in 1999 showed nebular emission out to $2''$ with the brightest knots within $0.5''$ of the central binary system (Eyres et al., 2001). Ground-based emission line images obtained with the Nordic Optical Telescope (NOT) under sub-arsecond seeing conditions revealed the presence of a $30''$ nebula, indicating an earlier episode of mass loss from the central system. Spectra obtained at the same time showed that the kinematics in the inner nebula was consistent with a rotating inner torus, while in the outer nebula there were a string of knots indicating episodic mass ejection (Corradi et al., 1999).

ISO spectra of HM Sge, obtained in 1996 and '97, clearly show the 10 and 18 μm silicate features (Fig. 2). The spectrum also shows a number of nebular lines, including those from highly-ionized species such as [Ne V] and [Ne VI], which indicate either a high effective temperature for the central source, or more likely, continuing shock activity (Schild et al., 2001).

Proposed Observations

We propose observations of HM Sge in wavelength regimes from the IR to the UV in order to study the circumstellar dust shell, the molecular flows, and the compact nebula surrounding the central engine. FORCAST photometry and spectroscopy in the mid-IR will allow us to characterize the silicate dust and provide us ionic emission lines to probe the nebular emission (Fig. 2). High spectral resolution observations with EXES of the H_2O molecular lines will yield the kinematics of the wind and the accretion flow. High angular resolution HST/WFC3 narrowband images in Hα, [N II] and [O III] will be used to reveal the morphology of the ionized gas and jet. An additional longer exposure in the F657N filter will reveal the morphology of the extended nebular emission. Changes that have occurred since the earlier epochs of observation will be examined at the sub-arcsecond scale to estimate the velocities of the jet outflow. Spectroscopy in the UV using COS will target the high ionization lines such as C IV and N V that are crucial probes of the shocked gas. By comparing the UV line strengths obtained with COS to those with IUE, we will track the long-term evolution of the shocks over a time baseline of 28 years.

Collectively, our data will be used to study the detailed dynamics of the system and to characterize its long term evolution as the system continues to relax decades after the explosion. Exposure times are listed in Table 1.

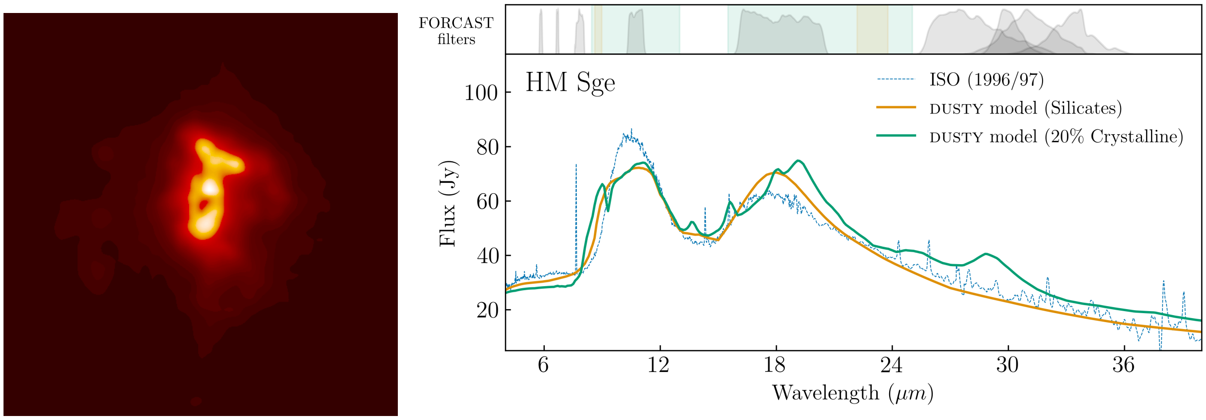

Figure 2 *Left*: A WFPC2 image of HM Sge from Eyres et al. (2001), showing an image of the extended nebular emission dominated by the [O III] lines at 5007Å. *Right*: The ISO spectrum of HM Sge from 1999 showing strong silicate emission at 10 and 18 μm. The spectrum is fit using the Dusty Evolved Star Kit[a] (DESK; Goldman et al. submitted). The proposed FORCAST imaging filters are also shown in gray (orange if profile unavailable) in the top panel. The wavelength range of the proposed grism observations are shown in the green shaded region.

Observing strategy and time estimates

FORCAST: FORCAST imaging and spectroscopy will be used to obtain continuum IR photometry and spectral coverage over the 10 & 18 μm silicate features. These features are sensitive to the optical depth and are critical for constraining the dust properties and production. Ionic emission lines will also be used to probe the nebular environment. We require imaging in all available bands and grism spectroscopy in the FOR_G111 and FOR_G227 bands. We have been advised by the SOFIA instrument team that we should allow a minimum exposure time per pointing of 30 seconds in our request, and 3 dithers per observation. We will use dual imaging to increase observing efficiency. For the grism spectroscopy, we need an SNR of at least 40 at the top and bottom of the silicate features. This requires exposure times using the FOR_G111 and FOR_G227 grisms of at least 300 and 100 seconds, respectively. The total exposure time including overheads calculated using SITE is 1 hour.

EXES: Using EXES we resolve individual ro-vibrational transitions arising from hot, dense H_2O, enabling the study of material very close to the central objects. This will allow us to study the inner kinematics and accretion flow of the system. We propose to use EXES in high medium mode (10^{th}–7^{th} order) for three to four spectral settings, which have central wavelengths of 5.72, 6.097, 6.73, and 7.5 μm, in order to target the $\nu 2$ band of H_2O. The average continuum level of HM Sge from ISO observations suggests the average continuum

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[a] The DESK is available at https://github.com/s-goldman/Dusty-Evolved-Star-Kit. The fit in this example uses radiative transfer models from the DUSTY code (Elitzur & Ivezić, 2001) using a grid of 100% oxygen-rich silicates (Ossenkopf et al., 1992), and another with 80% silicates and 20% crystalline silicates from Jaeger et al. (1994).

is about 35 Jy in this range, so these observations will be performed with the 3.23″ slit. This slit gives a spectral resolution (R ∼50,000) or a velocity resolution 6.0 km s^{-1}. The total time (including overheads) to obtain an SNR of $\gtrsim$75 is 3 hours.

WFC3/UVIS: We will compare previous NTT and WFPC2 observations to new WFC3 imaging to capture the morphology and do proper motion studies of outflows surrounding HM Sge. To detect changes in the spatial distribution of the nebular emission, we need sensitivity in the F502N([O III]), F656N(Hα), and F658N([N II]) filters similar or better than the previous observations. We will use three short exposures to image the inner nebula around the symbiotic system, and then a longer exposure that will saturate at the core, but that will capture the morphology of the more extended surrounding nebula. [O III] and Hα were previously observed with *HST*/WFPC2 (Eyres et al., 2001) with exposure times of 100 s. The [N II] line was observed with the NOT with exposure times of 90, 300, and 900×2 seconds (Corradi et al., 1999). In the F502N([O III]), F656N(Hα), and F658N([N II]) filters, to achieve an SNR of 5 at the $1.5{\times}10^{-14}$ ergs cm^{-2} s^{-1} Å $arcsec^{-2}$ level, we need 80, 65, and 58 second exposures, respectively. To capture the morphology of the nebular emission we will use the F658N([N II]) filter again. A 60 minute observation gives us an SNR of 5 at the level of 3×10^{-15} ergs cm^{-2} s^{-1} Å $arcsec^{-2}$, near the best conditions of the previous NTT observations ($\sim 10^{-15}$ ergs cm^{-2} s^{-1} Å $arcsec^{-2}$). We request 2 orbits to complete our scientific goals.

COS: We will compare new low-resolution COS NUV and FUV spectra to previous IUE spectra with similar wavelength coverage from 1982 (Nussbaumer & Vogel, 1990). The suite of lines observed come from a range of ionization states and allow us to probe the emission from both photoionized and shock-excited gas. The long-term evolution of these lines (and their ratios) will let us determine how the relative importance of each process has changed. We will use the G140L/800 (770–1950 Å) and G230L/2950 (1651–2049 & 2751–3150 Å) gratings that span a similar wavelength range as the previous observations, and will need an SNR of at least 10 for the ionization lines. At a minimum, we need to detect the [Ne V] line at 1575 Å in the FUV (with an expected flux of around $9.3{\times}10^{-14}$ ergs cm^{-2} s^{-1} Å) and the [Mg V] doublet around 2800 Å in the NUV (with an expected flux of around $1.4{\times}10^{-12}$ ergs cm^{-2} s^{-1} Å). Exposure times of 194 and 92 seconds, respectively, will give us an SNR of 10 at these levels. Due to the extended nature of the system we will need three exposures for each grating, one on the system, and two on the previously identified shocked regions to the North and South. We request 2 orbits to achieve our science goals.

Synergies and other Possible Observations

Observations that would further allow us to understand the complex environment of HM Sge would be with HAWC+, allowing us to study the polarization of the extended circumstellar environment, and with GREAT, giving us the opportunity to track the kinematics of other molecular line species in the complex flows occurring in the system. We note that other, brighter AGB stars have been imaged with HAWC+, and polarimetric observations are expected to have exposure times of several hours. With 4GREAT, it will be possible to tune one of the channels to [NII] 205 μm to see whether there is any emission from low-density nebular gas.

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Table 1 Exposure times for the proposed SOFIA and HST observations. Imaging SNRs and exposure times are calculated with respect to the previous archival observations (see the observing strategies and time estimates section).

Instrument	Filter/Grating	R	SNR	Dithers/ Exposures	t_{exp} (s)
FORCAST	All FOR_F (12)	-	> 10	3	30 s
FORCAST	FOR_G111	300	40	1	300 s
FORCAST	FOR_G227	140	40	1	100 s
EXES	7th order	50,000	75	1	19 m
EXES	8th order	50,000	75	1	58 m
EXES	9th order	50,000	75	1	64 m
EXES	10th order	50,000	75	1	58 m
WFC3	F656N (Hα)	-	> 10	1	65 s
WFC3	F658N ([N II])	-	> 10	1	58 s
WFC3	F502N ([O III])	-	> 10	1	80 s
WFC3	F658N ([N II])	-	5	1	60 m
COS (FUV)	G140L/800	2,000–5,000	10	3	194 s
COS (NUV)	G230L/2950	1,550–2,900	10	3	92 s