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Stratospheric Observatory for Infrared Astronomy Science Steering Committee

Supernova Remnants and the Life Cycle of Interstellar Dust

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Scientific category: INTERSTELLAR MEDIUM
Instruments: EXES, FLITECAM/CAM, FORCAST, FIFI-LS, HAWC, SAFIRE
Hours of observation: 110

Abstract

We propose to use the unique instrumental capabilities of SOFIA to conduct imaging and spectroscopic studies of supernovae (SNe), of young supernova remnants (SNRs) for which the ejecta have not yet fully mixed with the ISM, and select regions in older remnants which are interacting with the ambient ISM. These observations will address key issues within NASA's Visions for Science quest for discovering the origin, structure, evolution and destiny of the universe: What is the origin of dust in early universe? How efficient are supernovae in producing interstellar dust? How efficient are their blast waves in destroying, processing, or even forming dust as they expand into the circumstellar and interstellar medium? How do interstellar shocks facilitate chemical reaction on the surfaces of dust grains? The answers to these questions are crucial for understanding the evolutionary cycle of interstellar dust, the role of dust in the processing of starlight and in determining the thermal balance and chemistry of the ISM, and its role in the formation of protoplanetary objects. Our proposed observations will explore crucial stages of this evolutionary cycle, most readily observed at wavelengths between $\sim 5 - 300$ μm with spectral resolution from $\sim 30 - 3 \times 10^4$, and at spatial resolution of a few arcseconds, requiring therefore the unique capabilities of the different SOFIA instruments.

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Observing Summary:

Target	RA	Dec	F_{Jy}	Configuration/mode	Hours
SN1987A	5 35 27.87	-69 16 10.5	< 1	FLITECAM,FORCAST,HAWC	4
CAS A	23 23 26	+58 48	< 1	FLITECAM,FORCAST,HAWC	12
KEPLER	17 30 42	-21 29 3	< 1	FLITECAM,FORCAST,HAWC	6
TYCHO	00 25 18	+64 09	< 1	FLITECAM,FORCAST,HAWC	8
3C58	02 05 41	+64 49	< 1	FLITECAM,FORCAST,HAWC	8
CRAB	05 34 31	+22 01	< 1	FLITECAM,FORCAST,HAWC	8
SN1006	15 02 50	-41 56	< 1	FLITECAM,FORCAST,HAWC	8
G292.0+1.8	11 24 36	-59 16	< 1	FLITECAM,FORCAST,HAWC	10
PUPPIS A	08 22 10	-43 00	< 1	FLITECAM,FORCAST,HAWC	8
IC443	06 17 00	+22 34	< 1	FLITECAM,FORCAST,HAWC	8
CYGNUS LOOP	20 51 00	+30 40	< 1	FLITECAM,FORCAST,HAWC	8
SN1987A	5 35 27.87	-69 16 10.5	< 1	EXES, FIFI LS, SAFIRE	2
CAS A	23 23 26	+58 48	< 1	EXES, FIFI LS, SAFIRE	2
KEPLER	17 30 42	-21 29 3	< 1	EXES, FIFI LS, SAFIRE	2
TYCHO	00 25 18	+64 09	< 1	EXES, FIFI LS, SAFIRE	2
3C58	02 05 41	+64 49	< 1	EXES, FIFI LS, SAFIRE	2
CRAB	05 34 31	+22 01	< 1	EXES, FIFI LS, SAFIRE	2
SN1006	15 02 50	-41 56	< 1	EXES, FIFI LS, SAFIRE	2
G292.0+1.8	11 24 36	-59 16	< 1	EXES, FIFI LS, SAFIRE	2
PUPPIS A	08 22 10	-43 00	< 1	EXES, FIFI LS, SAFIRE	2
IC443	06 17 00	+22 34	< 1	EXES, FIFI LS, SAFIRE	2
CYGNUS LOOP	20 51 00	+30 40	< 1	EXES, FIFI LS, SAFIRE	2
				Grand total hours	110

Scientific Objectives

The overall objective of this proposal is to understand the origin and evolution of dust grains in the universe by studying the most important evolutionary phases in their life cycle through infrared observations of supernovae (SNe), of young and unmixed supernova remnants (SNRs), and of interaction regions of old remnants with the interstellar medium (ISM). The proposed observations of these targets cover the most important sites of dust formation, destruction, and processing, and are therefore crucial for addressing the following issues:
(1) the yield of dust in SN ejecta
(2) the yield of heavy elements in SN ejecta
(3) the survival of dust in the early SN environment
(4) the formation of dust in early SN environments
(5) the efficiency of grain destruction and processing in the interstellar medium
(6) the origin and evolution of dust in the early universe
(7) stellar evolutionary effects on the evolution of dust, and finally
(8) for young SNRs, IR echoes from the ambient ISM can constrain the SN event and the progenitor star.

Core collapse supernovae (SNe) are the primary source of heavy elements in the interstellar medium (ISM). They are also potentially important sources of refractory grain cores, if the condensible elements that formed in the explosion precipitate efficiently out of the expanding ejecta. Furthermore, the propagating SN blast waves are also an important agent of grain destruction and processing in the ISM. Thus, SNe play a major role in the evolution of dust and the depletion of gas-phase elements in the ISM of galaxies. The ideal objects for studying yields of dust and heavy elements from massive stars are young SNRs for which the ejecta have not yet fully mixed with the ISM. More evolved remnants will be used to study the destruction, processing, and possible formation of dust by shocks propagating through the general ISM.

Our list of target SNRs includes all of the historically observed Galactic SN, select regions in older remnants, as well as the remnant of SN1987A in the LMC, the most extensively studied remnant in the history of modern astronomy. Although the historical remnants were observed with the *Infrared Astronomical Satellite* (*IRAS*), *Infrared Space Observatory* (*ISO*), and the *Spitzer* satellite, SOFIA provides imaging capabilities over a broader range of narrow band filters wavelengths spanning the 1 to 240 μm wavelength region. Filter selection can be optimized for the detection of various dust species (carbonaceous, silicates, sulfides, or other dust species) in the ejecta. The broad wavelength coverage will also allow the detection of cold dust, which remained undetected in previous observations. SOFIA also offers higher spectral resolution which will allow us to examine various physical processes, such as the interaction of the ejecta with the ambient ISM, the velocity structure of the ejecta, and the processing of interstellar dust by the expanding SN blast wave in great detail. Figure 1 (top panel) depicts the various SOFIA instruments to be used for the proposed research.

Spectral imaging of young SNRs or specific interaction regions in evolved remnants will be used to construct the spatial distribution of dust mass, temperature, and composition. Comparison of the IR images with their radio, optical, and X-ray counterparts will be used to determine the dust origin and its heating mechanism (collisions, radiation). Detailed stochastic heating models will be used to determine the physical properties (size and temperature distribution, mass, composition) of the radiating dust, and the physical conditions (density, temperature) of the shocked gas or the intensity of the ambient radiation field. Also, the IR images will provide a clear view of the morphology of the SNR and its surrounding environment. Repeat observations of the environment around young SNRs may show variability in the IR emission and lead to the discovery of infrared echoes that will reveal details of the explosive SN event that created the remnant (e.g. Hines et al. 2004; Krause et al. 2005; Dwek & Arendt 2008).

The Yield of Dust in SN Ejecta - SNe and Young SNRs

Massive stars ($8 \lesssim M(M_\odot) \lesssim 120$) undergo core collapse and become supernovae (SNe), liberating about 10^{51} erg of nuclear binding energy and newly-synthesized elements into the interstellar medium (ISM). A fraction of the refractory elements precipitate out of the cooling ejecta, forming dust particles that are ejected into the surrounding medium as well. These dramatic explosions are responsible for the evolution of the metallicity and dust abundance in the ISM.

In general, SNe and young unmixed SNRs have been extensively studied at radio, UV/optical, and X-ray wavelengths. Radio observations trace the synchrotron emission component. UV and optical studies reveal the presence of high velocity filaments composed almost entirely of light and intermediate-mass metals such as O, Ne, or the S-Si group (S, Ar, Si, Ca). X-ray spectral images have traced S-Si and Fe group elements in the shocked ejecta. In Cas A, for example, both the optical and X-ray work have uncovered remarkable complexity in the structure and kinematics as seen in different elements, providing strong evidence for extensive mixing between different compositional layers during the explosion (Hughes et al. 2000, Hwang et al. 2000).

Dust was first detected in Cas A in the *IRAS* all–sky survey (see review by Dwek & Arendt 1992). With limited spatial resolution and only 4 broad spectral bands, *IRAS* observations gave an estimated dust mass of $\lesssim 10^{-3}\ M_\odot$, and were unable to determine the dust composition, or the origin of the emitting dust, whether it was shocked circumstellar or ejecta dust.

The *IRAS* observations suggested the existence of a good spatial correlation between the IR and X-ray emission, leading to the conclusion that most of the IR emission can be attributed to dust that is stochastically heated by the shocked X-ray emitting gas (Dwek et al. 1987). However, the *IRAS* measurements lacked the spatial and spectral resolution to distinguish between interstellar (swept-up), circumstellar, or SN-condensate dust.

Higher resolution 10.7–12 μm images of Cas A, obtained with the ISOCAM on board the *ISO* satellite, showed a correlation between the hot dust continuum and the optical line emission from heavy elements in fast moving knots, thereby unambiguously establishing their SN origin (Lagage et al. 1996). The *ISO* observations also showed that the dust in a limited area of the ejecta is composed of protosilicate material (Arendt et al. 1999). Dust temperatures derived from the *IRAS* and *ISO* data are $\sim$ 100–200 K, consistent with dust that is collisionally- or radiatively-heated in shocks. Total inferred dust masses are about 10^{-3} $M_\odot$, significantly below the mass of condensable elements expected to be present in the ejecta of a massive progenitor star (Woosley & Weaver 1995). Spectral mapping of the remnant with the *Spitzer*(Ennis et al. 2006; Rho et al. 2008) revealed the rich minerology of dust in the fast moving ejecta, as well as the abundances of trace metal-rich material which cools only through IR fine-structure lines. As a result of the *Spitzer* observations the estimated yield of dust in Cas A increased to 0.02 0.05 $M_\odot$, the range of values reflecting the uncertainties in dust composition. This mass is still much lower than the mass of refractory elements in the ejecta, and that needed to explain the origin of dust in the early universe.

The young SNRs selected for our studies consist of: **Cas A**, **Kepler** and **Tycho** - all historical remnants selected for searches for SN-condensed dust, dust heating mechanisms, the importance of IR versus X-ray cooling, and studies of grain destruction and procesing in shocks. **The Crab nebula** a historical remnant selected because of the detection of dust from extinction measurements. The dust in its nebula is heated by the nebular synchrotron emission, which in turn is energized by the Crab pulsar. The remnants **3C 58** and **SN 1006** were *not* detected by *IRAS*. **G292.0+1.8** is a slightly older remnant, interacting with its surrounding medium and a classic case for studying remnant evolution and interstellar dust processing in shocks.

SOFIA observations can further improve on the *Spitzer* results by providing higher spatial information and spectral coverage. These observations will resolve the ambiguities in the dust composition, and provide better correlation of the dust emission components with their UV-optical and X-ray counterparts. Such information will be used to construct physical models for the stochastic heating of dust by the ambient radiation field or hot plasma, which will provide a yet more accurate determination of dust mass.

The Yield of Heavy Elements in the SN Ejecta - - SNe and Young SNRs

IRAS observed Cas A in broad-band infrared filters which, as pointed out by Dwek et al. (1987), included potentially significant, but difficult to predict, contributions from several strong ionic lines, e.g. [Ar III] 8.99 μm, [S IV] 10.5 μm, and [Ne II] 12.8 μm line emission (Dwek et al. 1987). It took the higher spectral and spatial resolution of the *ISO* to directly measure these and other IR lines from heavy elements in the FMKs (Lagage et al. 1996). Spectroscopic observations of a few selected positions with the *ISO* SWS (Arendt, Dwek, & Moseley 1999) revealed strong emission lines of ions of O, Ne, Si, S, and Ar at high velocities (Fig. 2), firmly establishing their association with the FMKs.

The IR spectral region also contains numerous fine-structure lines of Fe and Ni (seen in SN 1987A by Moseley & Dwek et al. 1989), but escaped detection in Cas A by *ISO*. Fe was, however, detected by *Spitzer*, because of it better sensitivity spatial coverage (Ennis et al. 2006; Rho et al. 2008). With SOFIA we will look for lines of Fe ions from [Fe I] to [Fe IV], and also for other Fe-peak elements such as Ni, addressing the controversial issue of the apparently high Ni/Fe ratio deduced from optical lines in SNRs.

The Fe-rich knots are also the most likely site for discovering trans-iron elements created by neutron-capture reactions on Fe-peak seed nuclei. Dinerstein (2001) has identified IR lines as arising from elements such as Se (Z=34) and Kr (Z=36) in planetary nebulae, where they were enriched by the s-process during the AGB star phase (Péquignot & Baluteau 1994; Dinerstein 2001; Dinerstein & Geballe 2001). In Cas A, r-process isotopes of these and other trans-iron elements may be detectable with SOFIA some possible lines include [Ge II] 5.66, [Se III] 5.74, and [As II] 9.40 μm.

The optical, X-ray, and IR line emission from the shocked regions of the remnant provide only a lower limit on the mass of the ejecta, since a significant fraction of the ejecta may not have yet been swept up by the reverse shock. A tantalizing hint that much more cool, IR-line-emitting gas may be present comes from the detections of [O I] 63 μm and [O III] 52 and 88 μm emission in a few limited pointings with *ISO* (Unger et al. 1997).

The Survival of Dust in Early SN Environments - Young SNRs

On February 23, 1987, Supernova 1987A (SN 1987A), the brightest supernova since Kepler's SN in 1604, exploded in the Large Magellanic Cloud (LMC). About ten years thereafter, the energy output from the supernova became dominated by the interaction of its blast wave with the inner equatorial ring (ER), a dense ring of gas located at a distance of about 0.7 lyr from the center of the explosion, believed to be produced by mass loss from the progenitor star. The ER is being repeatedly observed at optical wavelengths with the *Hubble Space Telescope* (*HST*), at X-ray energies with the *Chandra X-ray Observatory*, at radio frequencies with the Australian Telescope Compact Array (ATCA), and in the mid-IR with the Gemini South observatory and the *Spitzer* observatory (see Dwek et al. 2008 for detailed references). Multiwavelength observations of the ER show that its morphology and luminosity are rapidly changing at X-ray, optical, infrared, and radio wavelengths as the blast wave from the explosion expands into the circumstellar equatorial ring, produced by mass loss from the progenitor star.

The morphological changes in its appearance in these different wavelength regimes reveal the progressive interaction of the SN blast wave with the ER. The interaction regions appear as hot spots in the *HST* images, representing the shocked regions of finger-like protrusions that were generated by Rayleigh-Taylor instabilities in the interaction of the wind from the progenitor star with the ER.

Mid-IR observations of the SN at 11.8 and 18 μm with Gemini-South (see Bouchet et al. 2006) have shown conclusively that the IR emission arises from the ER. The *Spitzer* observations lacked the spatial resolution, but provided the spectrum from which the mass, composition, and grain size distribution in the ER were determined (Dwek et al. 2008). These observations provided an important estimate of the dust formation efficiency in the wind of its massive (15–20 $M_\odot$) progenitor. Comparison with the X-ray observations have provided the first direct evidence of the ongoing destruction of dust in an expanding SN blast wave on dynamical time scales.

Detailed follow up observations are needed to follow the progression of the SN blast wave into the ring and determine the processing of the dust. These observations are crucial for determining the efficiency of the different gas-grain processes in hot X=-ray emitting plasmas. Based on two epochs of observations, Dwek et al. (2008) were able to compare the actual grain destruction efficiency in the hot gas with nominal adopted values. Much more extensive observations are needed for a more useful comparison of theory with observations.

Furthermore, in a decade or so, a reverse shock, already observed to be sweeping through the outer H-rich layers of the ejecta, will be propagating through the inner metal- and dust-rich layers, providing a once-in-a lifetime opportunity to determine the mass of dust that formed in the SN, and to study the survival of the newly-formed dust as it encounters this reverse shock.

Shock Induced Dust Formation Formation by SN Blast Wave - Young SNRs

SN blast waves can become strongly radiative shortly after the explosion when they encounter very dense circumstellar material formed by extensive mass loss from the progenitor star. Recently, Smith et al. (2007) presented evidence for the formation of dust in the in the late-time spectrum of SN2006jc. The progenitor star underwent an LBV-type eruption 2 years before the SN event, creating a dense circumstellar environment around the star. Smith et al. proposed that the dust formed by the interaction of the SN blast wave with the dense circumstellar shell. The post-shock cooling compressed the shell to densities of $\sim 10^{10}$ cm^{-3}, providing the necessary physical condition for the formation and growth of dust. At present, it is not clear if the dust is the result of growth on pre-existing dust grains that were formed during the mass loss phase, or that the dust nucleated in a dust-free environment. Either way, these observations provide further evidence for the shock-induced formation of dust in circumstellar environments, previously observed in the shocked winds of WR stars in binary systems (Monnier et al. 2007).

Grain Processing in the General ISM - Evolved Remnants

The fate of dust particles swept up by interstellar shocks depends on the shock velocity, and on the density and composition of the preshocked medium in which the dust resided. Thermal and kinetic sputtering are the dominant grain destruction process in fast shocks ($v_{sh} \gtrsim 200$ km s^{-1}), vaporizing grain-grain collisions in intermediate velocity shocks ($v_{sh} \sim$ 50 to 200 km s^{-1}), and shattering grain-grain collisions dominate in low velocity shocks ($\lesssim$ 50 km s^{-1}) when the relative velocities between colliding dust grains are not large enough to vaporize them, but high enough to shatter them into smaller fragments (Jones 2004). These small fragments of dust can re-accrete the refractory elements from the gas phase as the gas cools down and is compressed to higher densities.

Evolved remnants are ideal objects for studying the physics of gas-grain and grain-grain interactions. Unlike ejecta dominated young remnants such as Cas A, Kepler, Tycho, and the Crab Nebula, they have resolved spatial structures, and exhibit a wide range of shock velocities and morphologies resulting from their interactions with distinctly different phases of the ISM. These evolved remnants are responsible for the bulk of the shock processing of interstellar dust.

For example, Puppis A (see Figure 1, bottom panel) provides an ideal remnant for such studies because of a unique combination of: resolved spatial structure; strong interaction with a CO and HI cloud complex with a well understood viewing geometry; a large sampling of shock velocities and plasma conditions; and a broad range of exquisite complementary observations at X-ray and UV wavelengths. The Bright East Knot (BEK, see white box in the figure) is a distinct example of fast shock engulfing an ISM cloud. It displays a relatively clean geometry edge-on geometry. It has a complex structure in X-rays and some optical filaments/knots that are not revealed in IRAS data (no *ISO* data or useful MSX coverage exist). The right panel of the figure shows an optical [OIII] image of the BEK. The rectangular box in that image encloses an optical filament, which will be well resolved with SOFIA instruments.

The Origin of Dust in the Early Universe

Quasars and galaxies detected at redshifts $z \gtrsim 6$ and observed at far infrared (IR) and submillimeter wavelengths exhibit luminosities in excess of $\sim 10^{13}\ L_\odot$, and inferred dust masses and star formation rates in excess of $\sim 10^8\ M_\odot$ and of $\sim 10^3\ M_\odot\ \mathrm{yr}^{-1}$, respectively (see Dwek et al. 2007 for references). These dusty hyperluminous galaxies provide unique environments for studying the role of massive stars in the formation and destruction of dust. At redshifts above ~ 6, when the universe was less than ~ 1 Gyr old, dust could have only condensed in the explosive ejecta of core-collapse SNe, since most of the progenitors of the AGB stars, the major alternative source of interstellar dust, did not have time to evolve off the main sequence. Models for the evolution of dust (Dwek et al. 2007) show that an average supernova must condense at least 1 $M_\odot$ of dust to account for the observed dust mass in SDSS J1148+5251, a dusty quasar at $z = 6.4$. This mass is in excess of the largest dust yield of $\lesssim 0.02\ M_\odot$ found thus far in the ejecta of any SN. If future observations find this to be a typical supernova dust yield, then additional processes, such as accretion onto preexisting grains, condensation in strongly cooling shocks, or condensation in AGN winds will need to be invoked to account for the large amount of dust in this and similar objects.

Stellar Evolutionary Effects on the Evolution of Dust

Nearby galaxies exhibit a wide range of global properties, such as their stellar and interstellar medium (ISM) masses, metallicities, and spectral energy distributions (SEDs). Considering metallicity as an indicator of galactic age, these galaxies can be considered as snapshots of their evolution at different epochs.

An exciting result provided by *ISO* spectral observations of nearby galaxies was the discovery of a striking correlation between the strength of their mid-IR aromatic features, commonly attributed to emission from polycyclic aromatic hydrocarbons (PAHs), and their metallicity (Madden et al. 2006). Low-metallicity galaxies exhibited very weak or no PAH features. Observations of the 8-to-24 μm bands flux ratio obtained with the *Spitzer* IRAC and MIPS instruments showed a correlation of this flux ratio with the galaxies' oxygen abundance (Engelbracht et al. 2005), confirming the trends discovered by the *ISO*.

Several interpretations have been given for this correlation: (1) Noting that the PAH-to-continuum intensity ratio correlates with the [NeIII]/[NeII] line ratio, which is a tracer of the young strongly ionizing stellar population, Madden et al. (2006) suggested that the paucity of PAH emission at low metallicity reflected their destruction by hard UV photons that are especially effective in destroying PAHs in dust-deficient environments; (2) O'Halloran et al. (2006) noted that the PAH-to-continuum intensity ratio correlates with the [FeII]/[NeII] line ratio as well. This line ratio is a tracer of interstellar shocks, suggesting that PAHs are more efficiently destroyed by shocks in low metallicity systems.

All previous explanations attribute the paucity of PAHs to destructive processes that are more efficient in the early stages of galaxy evolution. In contrast, Dwek (2005) suggested that the observed correlation reflects an evolutionary trend of the sources of interstellar PAHs with metallicity. PAHs and carbon dust are mostly produced in asymptotic giant branch (AGB) stars which, unlike massive stars, recycle their ejecta into the ISM after a significantly longer time of main sequence evolution. This hypothesis was investigated in detail by Galliano, Dwek, & Chanial (2007). Using chemical evolution models to follow the evolution of dust abundance and composition, their models show that the observed correlation of PAH line intensities with metallicity can be interpreted as a trend of PAH abundance with galactic age, reflecting the delayed injection of PAHs and carbon dust into the ISM by AGB stars in their final, post-AGB, phase of their evolution. However, the destruction mechanisms described above will play a role in the evolution of PAHs once they are injected into the ISM.

The model calculations can be considerably improved with more detailed knowledge about the grain destruction efficiencies in interstellar shocks. PAHs may also be created in shock by the hydrogenation of very small graphite grains created in shattering grain-grain collisions. However, AGB stars are still needed to form the bulk of the interstellar carbon that may form the PAHs in the ISM. The relative importance of this potential source of PAHs, compared to AGB stars, is currently unknown, but can be determined by the proposed observations of older SNRs.

Infrared Echoes Reveal Explosive Events of the Past

The great serendipitous discovery of infrared echoes around the Cas A supernova remnant with the *Spitzer* satellite (Krause et al. 2005) has provided astronomers with an unexpected opportunity to study the properties of the echoing material and the history and nature of the outburst that generated these echoes. In retrospect, the echoes are also clearly visible as infrared "hot spots" in *IRAS* images of the region. The spectra of the echoes are distinct from that of the dust in the general diffuse interstellar medium (ISM) revealing hot silicate grains that are either stochastically heated to temperatures in excess of ~ 150 K, or radiating at an equilibrium temperature of this value. Dwek & Arendt (2008) showed that the maximum luminosity that can be generated by the radioactive decay of ^{56}Ni is not capable of producing such spectra, and could therefore not have given rise to the echoes. Instead, they found that the echoes must have been generated by an intense and short burst of EUV-UV radiation associated with the breakout of the shock through the surface of the exploding star. The Cas A echoes represent the first indirect "view" of a shock breakout via the thermal dust emission from echoing clouds.

SOFIA will be able to follow up on these observations by repeat imaging observations of the surroundings of Cas A and other SNR, searching for variability in the diffuse ISM as the telltale signatures of the IR emission generated by the radiative SN outburst as it sweeps through the ISM.

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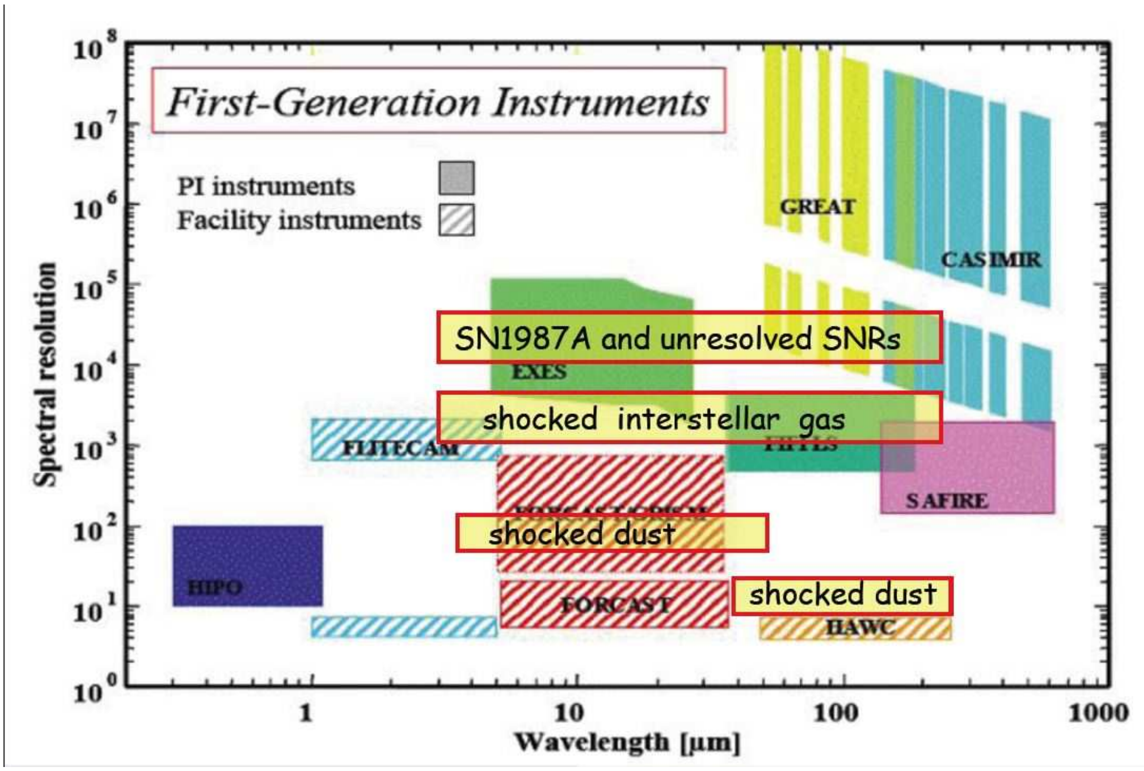

Figure 1: The different SOFIA instrument to be used for the proposed research. Low resolution spectra ($\lambda/\Delta\lambda \approx 10 - 50$) are generally sufficient for determining the dust composition and PAH features. Intermediate resolution ($\lambda/\Delta\lambda \approx (1 - 3) \times 10^3$)is needed to resolve atomic lines in fast shocks, and high resolution ($\lambda/\Delta\lambda > 3000 - 30,000$) is needed to determine the velocities of gas species behind low velocity shocks.

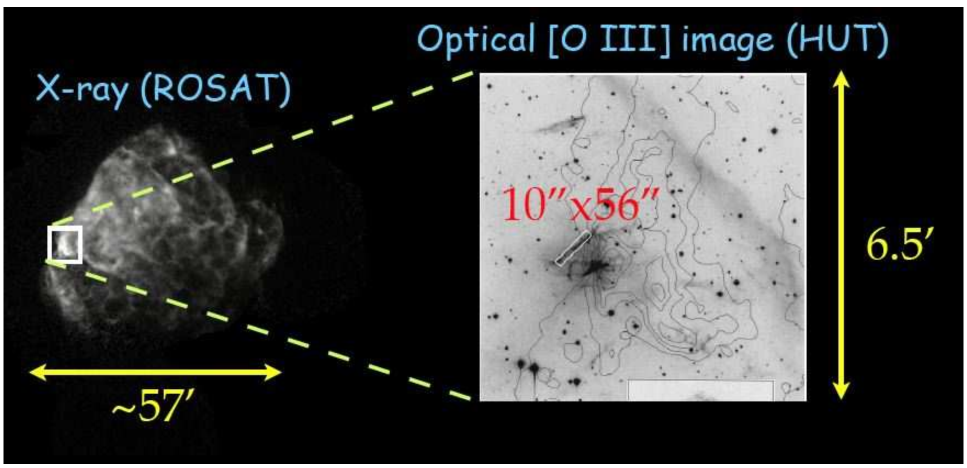

Figure 2: **Left image:** ROSAT image of Puppis A (Hwang et al. 2005). The white square covers a region that has been extensively mapped in X-rays, and UV. **Right image:** Optical [O III] image of the region enclosed by the white box in the left panel (Blair et al 1995). The rectangle encloses the area of an optical filament. The figure shows how high resolution spectral mapping of select regions in middle-aged and old remnants can be used in conjunction with X-ray and UV-optical observations to study the processing of interstellar dust in such environments.

SOFIA Uniqueness/Relationship to Other Facilities

SOFIA has unique capabilities compared to *Herschel* and *JWST*

1. SOFIA will provide almost simultaneous observations over a large range of wavelengths. This continuity is essential for observing rapidly evolving SNe and SNRs such as SN1987A, Cas A, or the Crab Nebula, as well as transient phenomena like light echoes. This information cannot be assembled by combining data from past (*Spitzer*, *ISO*) or future missions such as *Herschel* or *JWST*. These mission span over a decade in time, however, none of them have been or will be operational at the same time.

2. Compared to *Herschel* SOFIA will provide 5-60 μm wavelength coverage which is an essential diagnostic of emission from PAHs and small grains with temperature fluctuations. These grains are an essential diagnostic of grain composition and destruction in shocks.

3. SOFIA will be much better suited than *JWST* for mapping out extended regions, such as evolved SNRs and light echoes, which are much larger than the instrument FOV on either telescope.

4. The higher spectral resolution, compared to *Herschel* or *JWST*, attainable by SOFIA enables identification of the velocities of the emission lines. This is essential for identifying the kinematic structure of SNRs and distinguishing shocked regions from the general ISM. Knowledge of the shock speed is necessary for modeling the physical conditions of the gas and dust producing the line and continuum emission. The high spectral resolution is particularly useful for studying old SNRs and the interaction of shocks with dense circumstellar/interstellar material, where shock speeds fall below ~ 50 km s^{-1}.

5. SOFIA is well suited for studying SNRs embedded in bright regions of the Galactic plane, where bright backgrounds may saturate the detectors on *JWST*, which is designed to look for the faintest objects in the universe.

The wide wavelength coverage of SOFIA's suite of imaging instruments will provide *complete* coverage all dust components that may be present. This includes emission from PAHs at 3 - 15 μm, "typical" silicate and carbonaceous grains at mid-IR wavelengths, and elusive very cold grains at far-IR wavelengths. Furthermore, the wide selection of filters available with SOFIA's instruments allows the imaging to be targeted to particular spectral features (e.g. silicate peaks), that will allow much better diagnositics of the IR emission mechanisms than are available from the few generic broad provided by Spitzer's IRAC and MIPS instruments. The good spatial resolution is also essential feature of SOFIA's imaging. SNRs tend to be in crowded complex fields where confusion with foreground and background emission can easily obscure a remnant when observed at lower spatial resolution (e.g. IRAS). Obtaining IR data at few arsecond resolution is also extremely valuable for cross correlation of the IR data with X-Ray, optical, and radio data.

Spectroscopy of SNRs from SOFIA will similarly benefit from the broad wavelength coverage. This coverage will allow the detection of multiple lines of many elements in several different ionization states (e.g. [O I], [O III], [O IV]). The far-IR coverage is particularly important for observations of C, N, and O, and is only partially provided by Spitzer's MIPS SED mode at low spectral resolution. Mid- and near-IR coverage is important for line emission diagnostics as well as dust spectral features.

Observing Strategy

Special Requirements

Maximum water:	low
A deployment is required to:	NZ

Precursor/Supporting Observations

Existing data obtained by IRAS, ISO, Spitzer, HST, 2MASS, MSX, Rosat, ASCA, XMM, and Chandra will be used to analyze SOFIA data. SOFIA data will be important for potential follow up observations with Herschel.