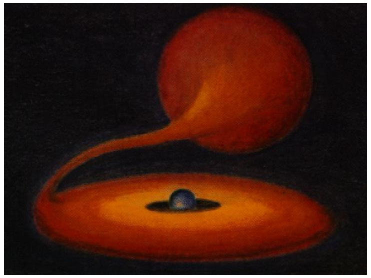
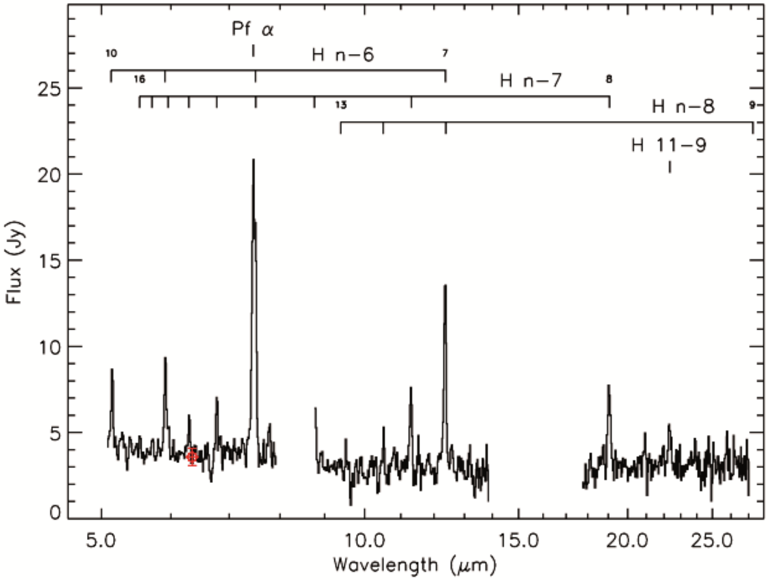
Infrared Observations of Novae in the SOFIA Era





R. D. Gehrz

Minnesota Institute for Astrophysics, University of Minnesota, USA

The SOFIA Target of Opportunity Nova Team

- PI: R. D. Gehrz, University of Minnesota
- Co-I's:

A. Evans, University of Keele, UK

Charles E. Woodward and D. Shenoy, University of Minnesota

N. M. Ashok and D. P. K. Banerjee, Mt. Abu Observatory, India

S. Eyres and M. Rushton, University of Central Lancashire, UK

L. A. Helton, USRA/SOFIA

L. Keller, Ithaca College

Joachim Krautter, Landessternwarte Heidelberg, Germany

T. Liimets, University of Tartu, Estonia

S. S. Mohamed, South African Astronomical Observatory, RSA

G. Schwarz, American Astronomical Society

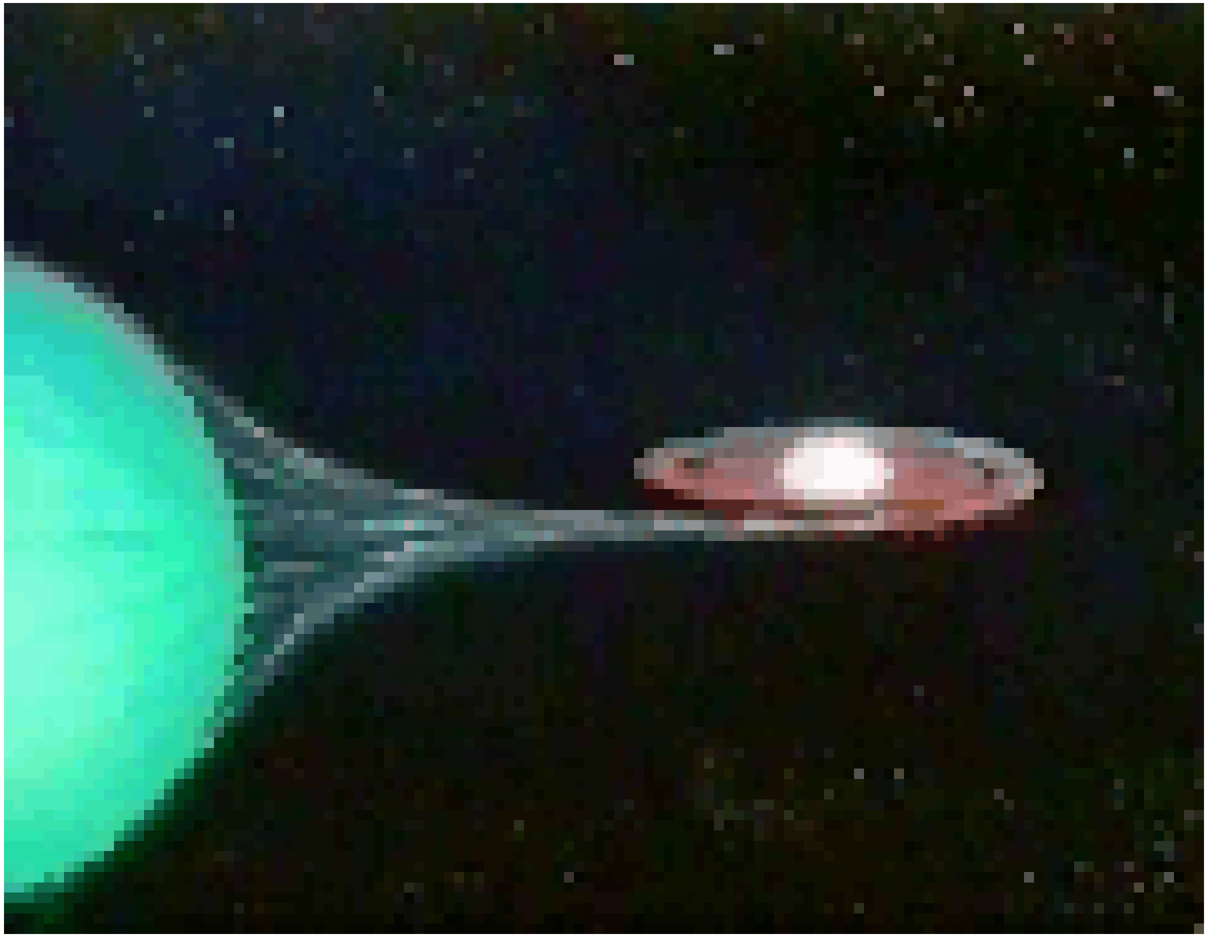
S. G. Starrfield, Arizona State University

R. M. Wagner, Large Binocular Telescope Observatory

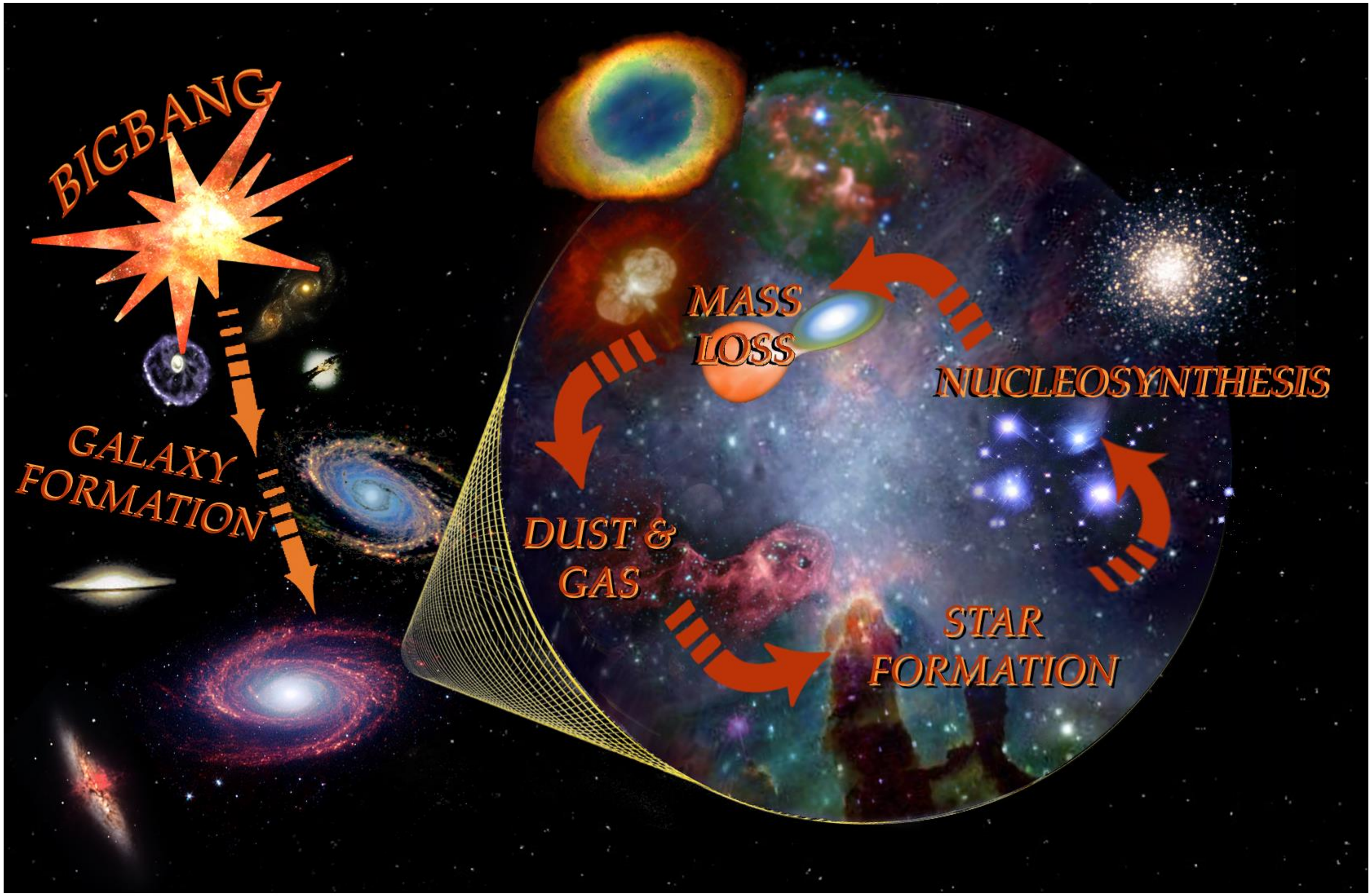
Outline

- Novae and Galactic chemical evolution
- Post outburst IR development of novae
- IR Observations of gas and grains in nova ejecta
- IR observations of novae with SOFIA
- Prospects for nova observations with LBT and JWST
- Summary

A Classical Nova Explosion: Accretion followed by a TNR



The Role of Classical Novae in Galactic Chemical Evolution



Classical Novae and Abundance Anomalies

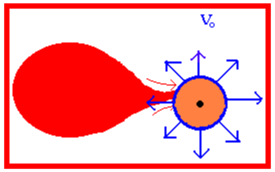
CN TNR theory predicts that CNe may be as important as SNe in affecting global ISM abundances of certain isotopes*:

- CNe process ≈ 0.3% of the ISM
- 50 yr^{-1}: $[dM/dt]_{CNe} \approx 7 \times 10^{-3}\ M_{\odot}\ yr^{-1}$
- 0.01 - 0.02 yr^{-1}: $[dM/dt]_{SNe} \approx 6 \times 10^{-2}\ M_{\odot}\ yr^{-1}$

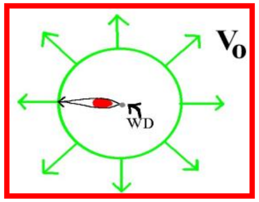
Conclusion: CNe may be important on a global Galactic scale if they produce isotopic abundances that are ≥ 10 times SN abundances and ≥ 100 times Solar abundances

******See, for example: Gehrz, Truran, and Williams 1993 (PPIII, p. 75),*
Gehrz, Truran, Williams, and Starrfield 1998 (PASP, 110, 3),
Evans and Gehrz, 2012 (BASI, 40, 213)

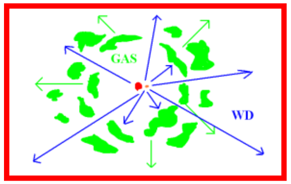
How the IR Shows what Nova Explosions Make



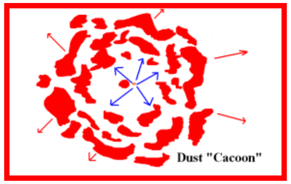
New elements are synthesized in the explosion



The ejected material is expelled into the Interstellar Medium where it is incorporated into new stellar and planetary systems

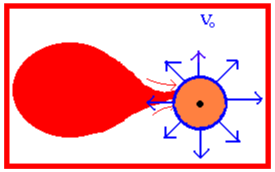


IR line emission from gas

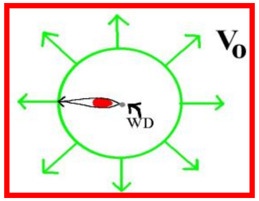


IR thermal emission from dust

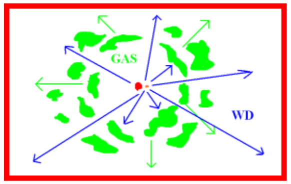
Infrared Development Phases



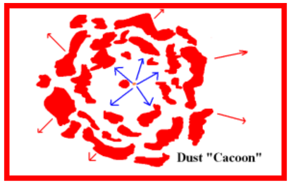
Fireball Expansion Phase



Free-Free Emission Phase

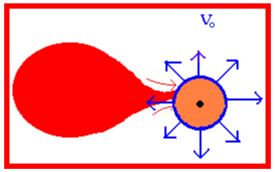


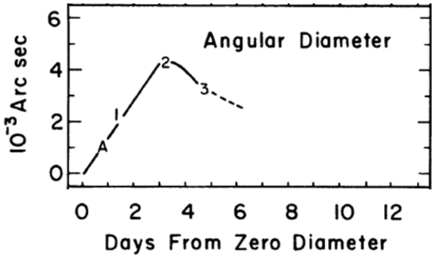
IR Forbidden Line Emission Phase in ONeMg Novae



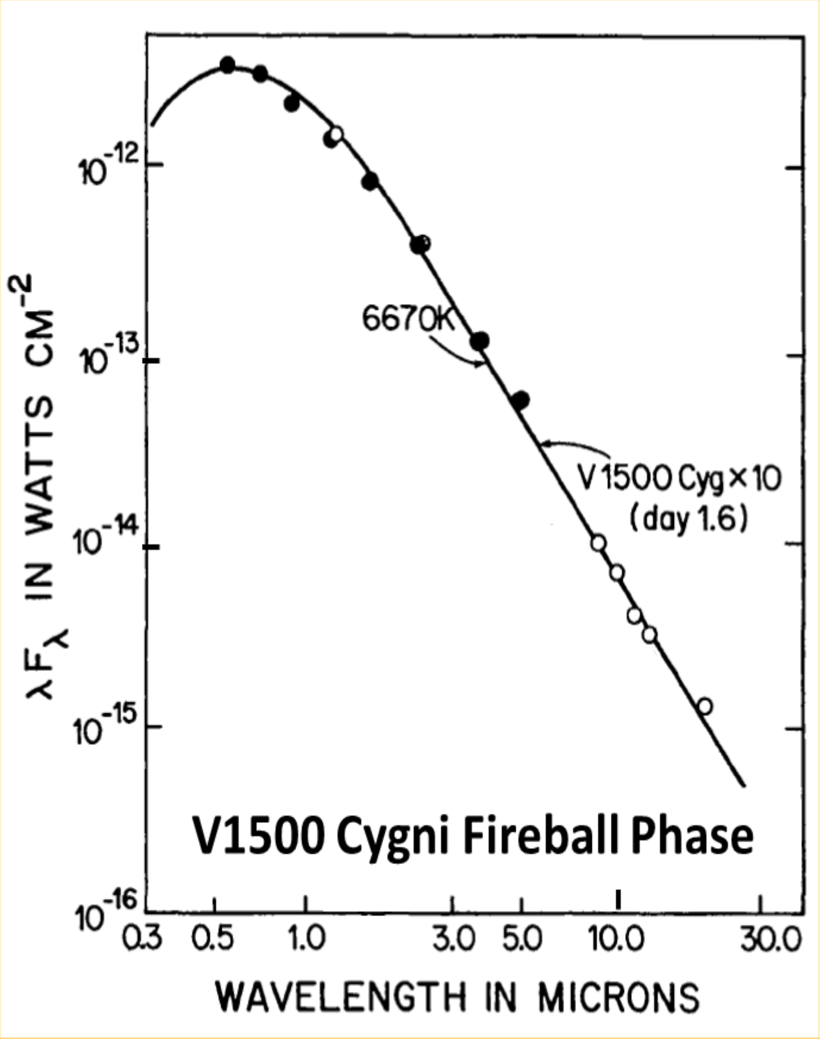
IR Dust Emission Phase Phase in CO Novae

The Fireball Expansion Phase





Gallagher & Ney 1976



Gallagher & Ney 1976

- The blackbody angular radius and Doppler expansion velocity give day zero, the distance, and the outburst luminosity:

$$\mathbf{D} = \frac{\mathbf{V_{out}t}}{\theta_{BB}(t)}$$

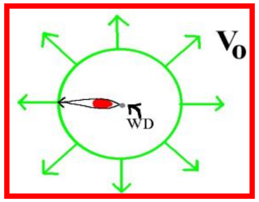
$$\mathbf{L_o} = 4\pi\mathbf{D}^2 \times (1.36[\lambda\mathbf{F}_\lambda]_{\mathbf{max}})$$

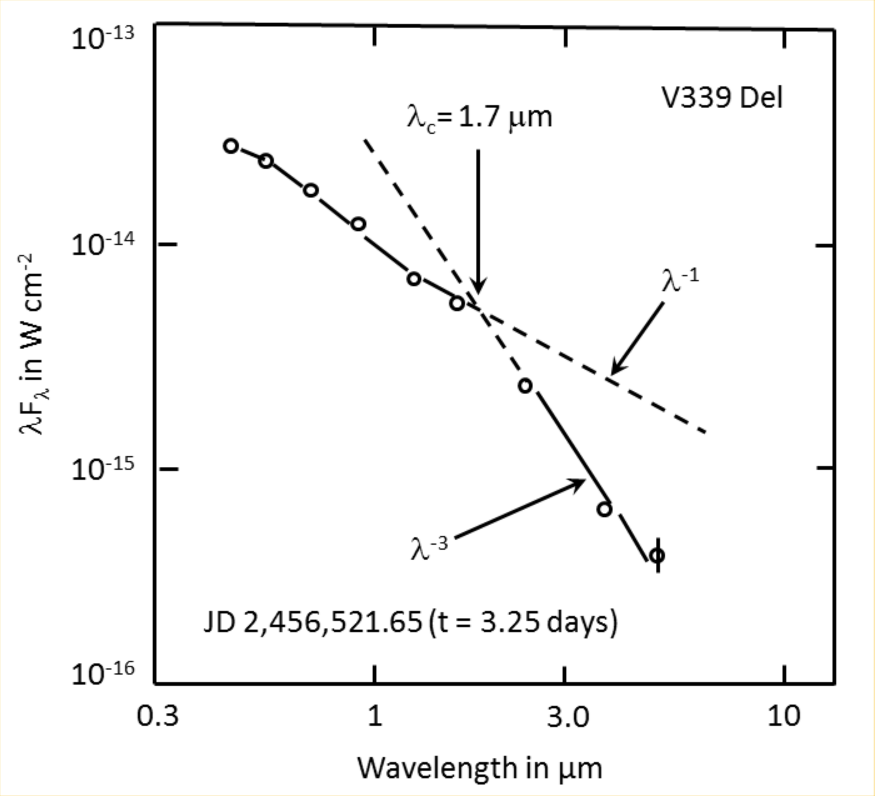
- The luminosity of the outburst fireball is $L_o \geq L_{Edd}$

The Blackbody Angular Radius

- Let $f = (1.36[\lambda F_\lambda]_{max})$ be the flux measured at Earth, D be the distance to the nova, and R = V_ot be its radius at time t after the explosion
- $L = 4\pi D^2 f = 4\pi R^2 \sigma {T_{BB}}^4$
- So the angular radius is $\theta_{BB} = \frac{R}{D} = \left[\frac{f}{\sigma {T_{BB}}^4}\right]^{1/2}$

Free-Free Expansion Phase

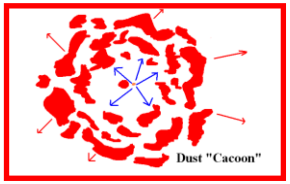


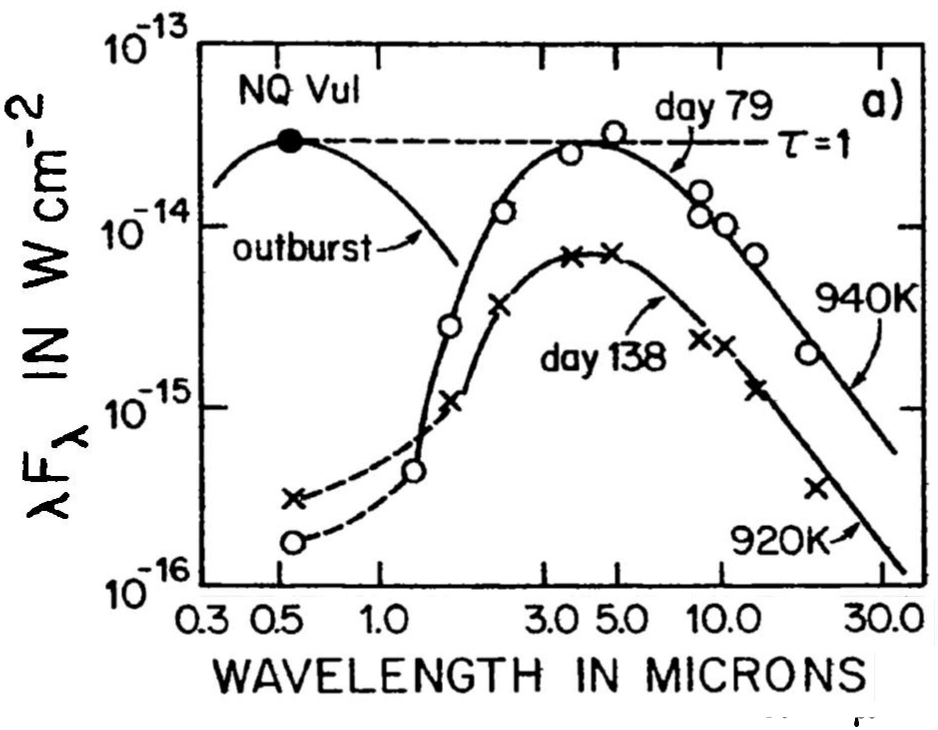


R. D. Gehrz, et al. 2015, ApJ, 812, 132

- The cut-off wavelength, λ_c, where the optical depth is unity gives the shell density, n_H, and the mass of the ionized ejecta (R. D. Gehrz, J. A. Hackwell, and T. W. Jones 1974, ApJ, 191, 675)
- $M_{gas} = \frac{4\pi}{3} n_H m_H (V_o t)^3$

Dust Formation Phase



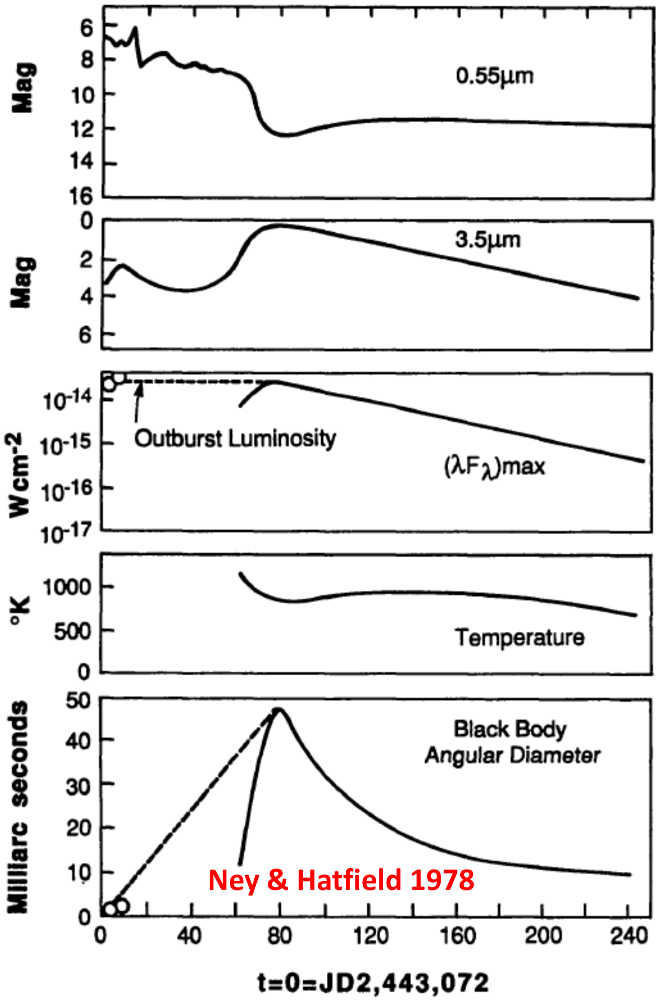


R. D. Gehrz (1988)

- The mineralogy of the dust is diagnosed by the thermal IR SED
- $L_o \geq L_{Edd} = L_{IR}$ for optically thick dust shells $\Rightarrow L_o$ = constant for a long time
- The gas to dust ratio can be used to deduce abundances of the condensibles

Dust Condensation in CO Novae

NQ Vul



Ney & Hatfield 1978

$$L_o \approx L_{Eddington}$$

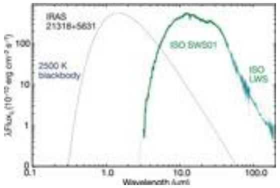
$$T_c \approx 1000\ K$$

$$R_C = \left[\frac{L_O}{16\pi\sigma T_C^4}\right]^{1/2}$$

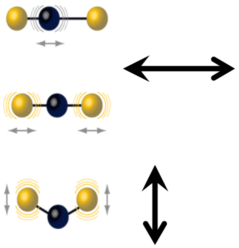
$$t_C \approx \frac{R_C}{V_O}$$

Infrared Spectra of Astrophysical Dust Grains

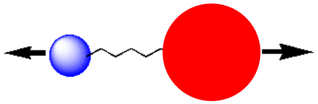
- Carbon and iron: Smooth emissivity



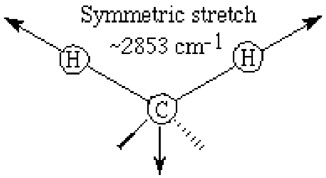
- Silicates: SiO_2 bond stretching and bending vibrational mode emission at 10 μm and 20 μm

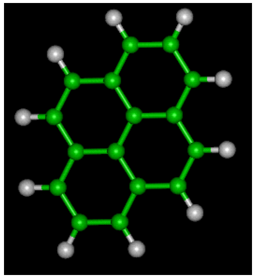


- Silicon Carbide: SiC stretching vibrational mode emission at 11.3 μm



- Hydrocarbons (HAC and PAH): C-H stretching and bending at 3.3 μm, C-C stretching modes at 6 - 18 μm, drumhead modes at longer wavelengths



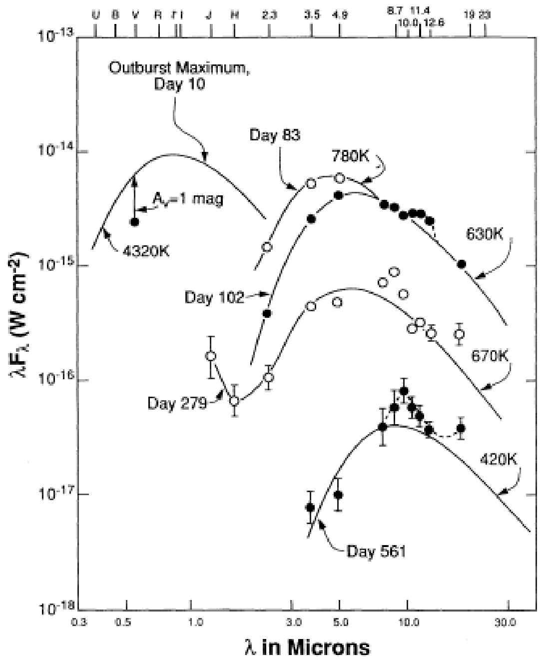


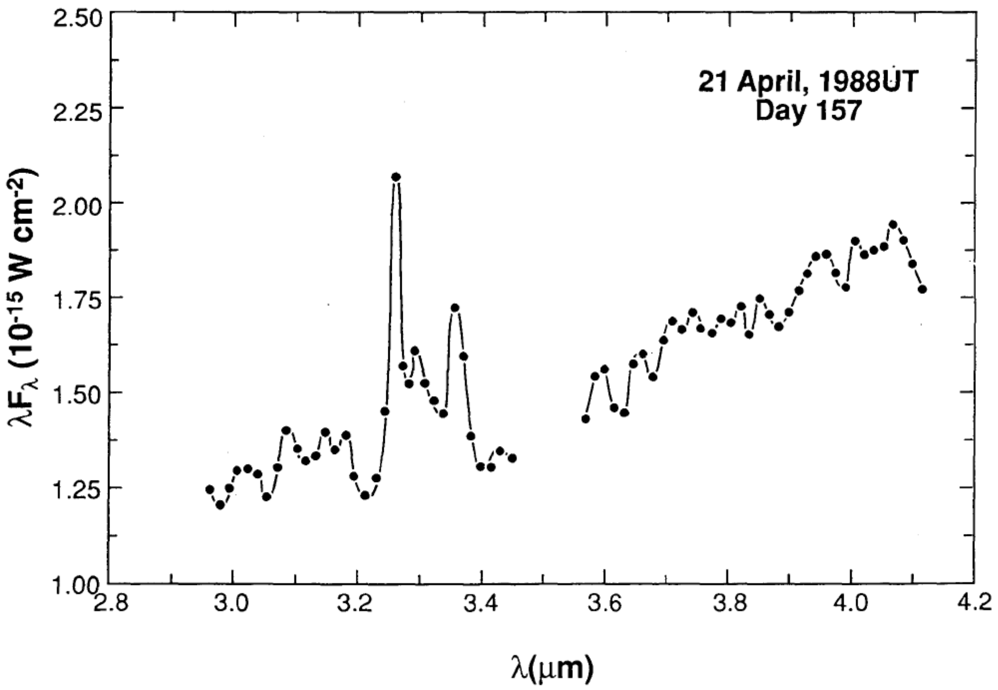
Nova Dust

- A small fraction (~20%) of classical novae form dust
- Novae produce carbon, SiC, silicates, and hydrocarbons
- Extinction event depths imply that the grains grow to radii of 0.2-0.7μm
- Dust mass, M_{dust}, can be derived from visual opacity, IR opacity, and IR emission feature strengths
- Abundance of condensed material is given by the dust to gas ratio, M_{dust}/M_{gas}

Multiple Grain Compositions in a Single Nova: QV Vul

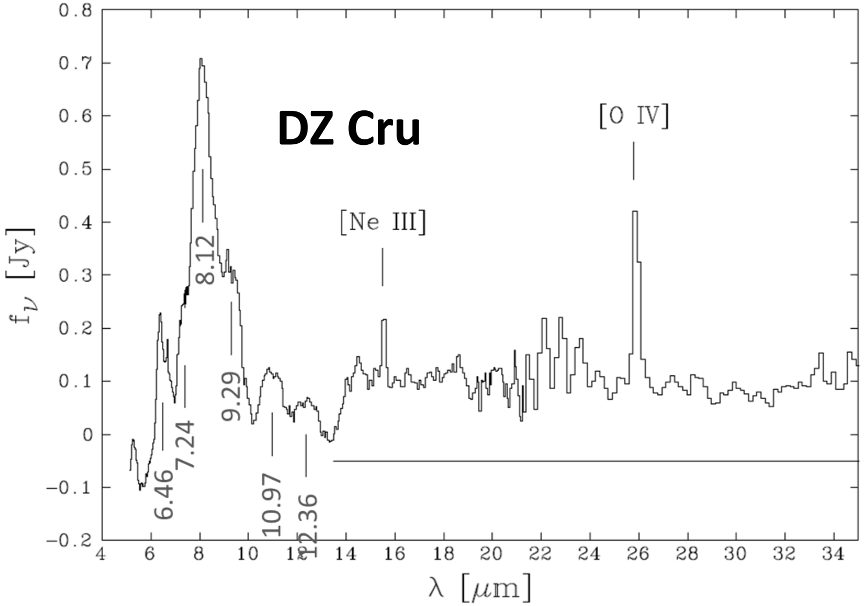
Gehrz et al. 1992 (Ap. J., 40, 671)





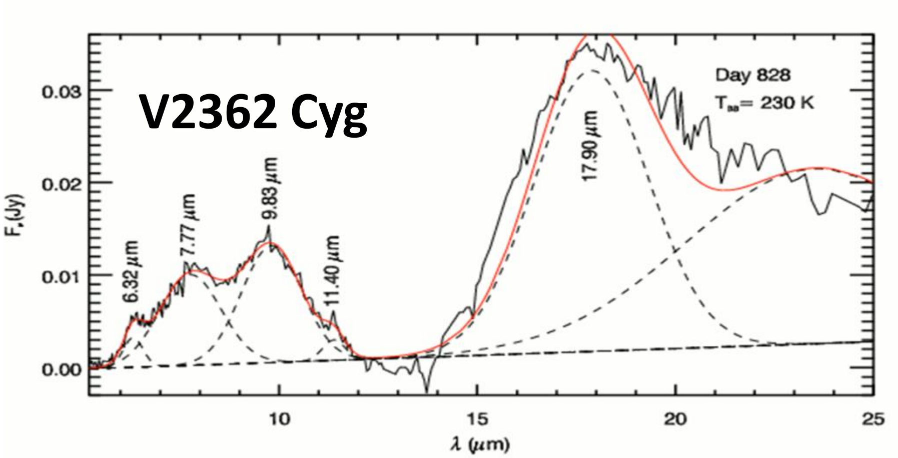
- Carbon, Silicates, SiC, and PAH grains formed at different epochs in QV Vul suggesting abundance gradients in the ejecta.
- A. D. Scott (2000, MNRAS, 313, 775-782) has shown that this could be explained by an asymmetric ejection due to a TNR on a rotating WD

Spitzer Spectra of Hydrocarbon Grains in CNe

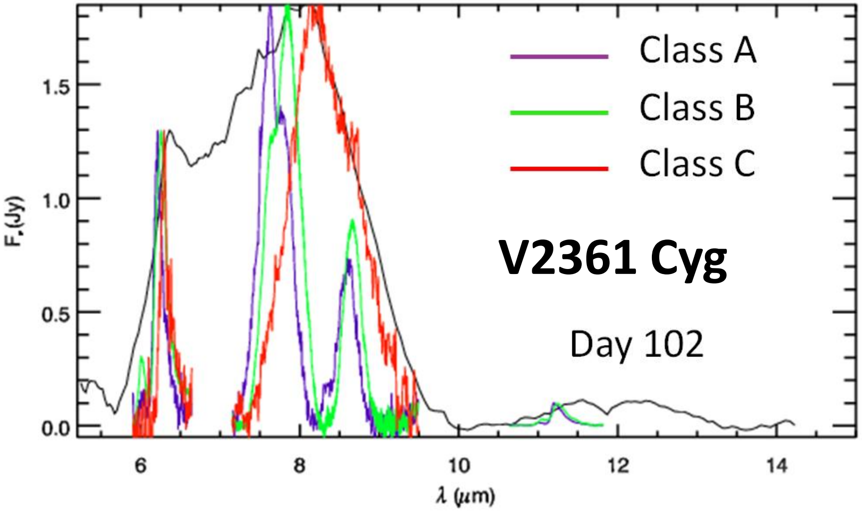


After A. Evans, et al. 2010, MNRAS, 406, L85

- **Hydrocarbon UIR emission features are required to fit the IR spectra in detail**
- **The best fit is for Class C PAH's as described by E. Peeters et al. 2002, A&A, 390, 1089**

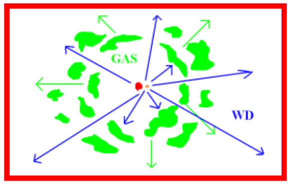


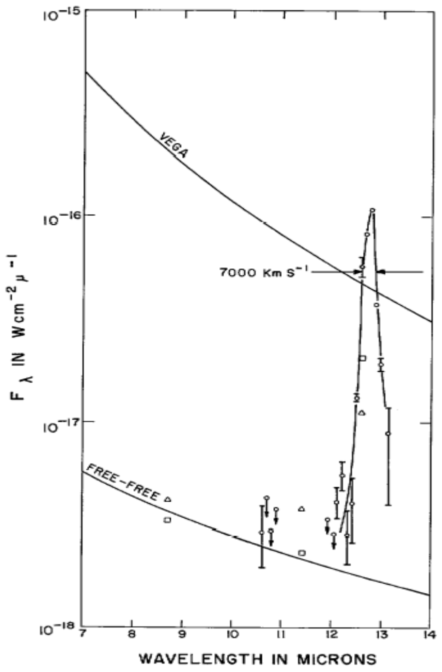
See L. A. Helton, et al. 2011, EAS Publications Series, 46, 407



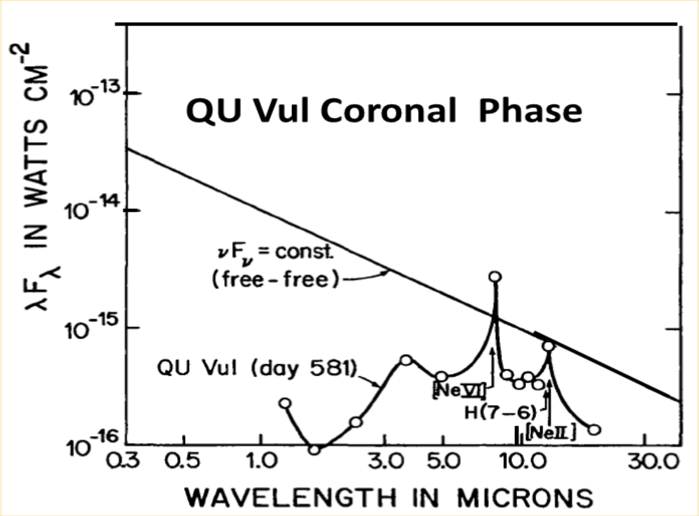
See L. A. Helton, et al. 2011, EAS Publications Series, 46, 407

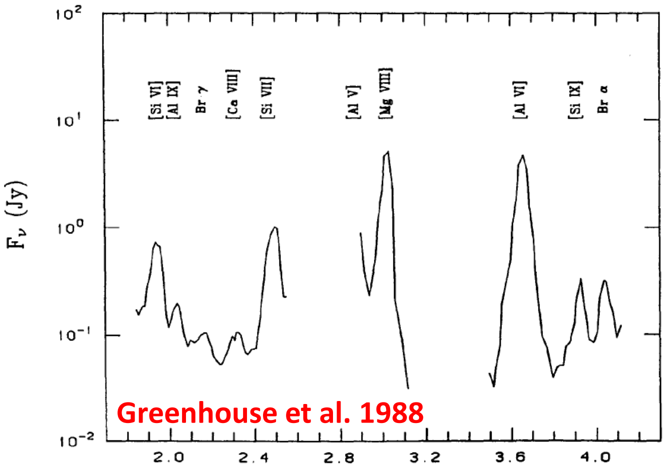
IR Forbidden Line Emission Phase





Gehrz et al. 1985

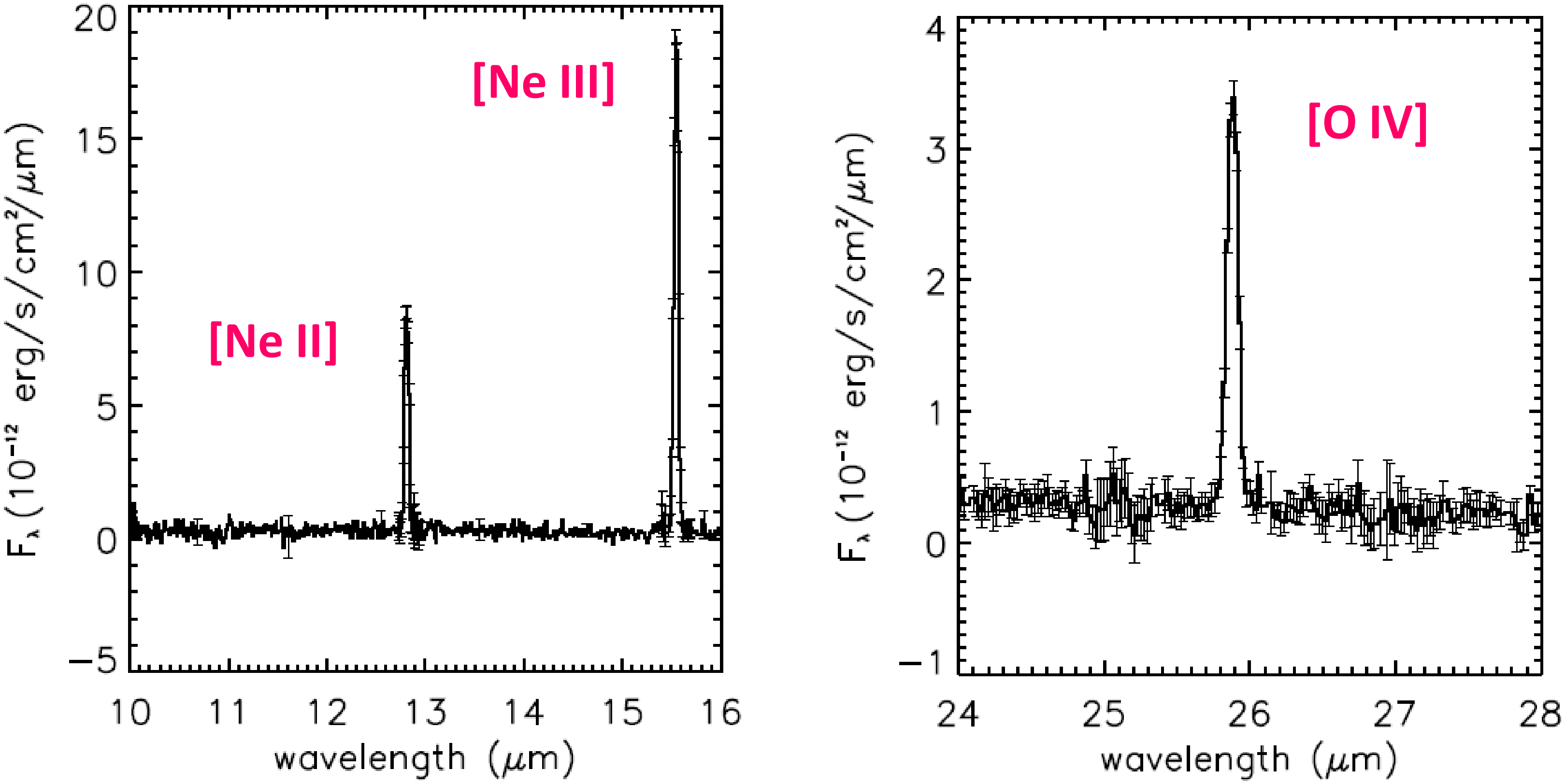




Greenhouse et al. 1988

- Strong metallic forbidden lines dominate the IR spectrum
- Lines strengths give lower limits to the metal abundances
- Excitation energy and velocity structure of the lines give information about the shell structure and dynamics

Spitzer IRS Spectra of Nova QU Vul
20 Years after Outburst

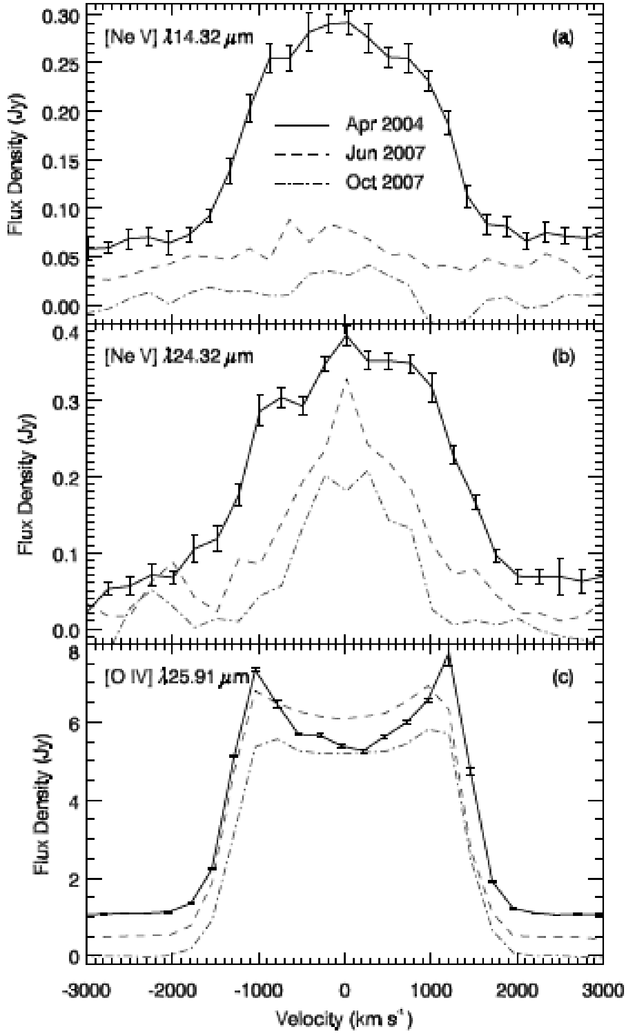


IRS Short-High **IRS Long-High**

R. D. Gehrz, et al. 2008, ApJ, 672, 1167

Velocity Resolved *Spitzer* Spectra:V1494 Aql

Line shapes reveal kinematic structure associated with different ionization potentials



L. A. Helton, et al. 2012, ApJ, 755, 37

Determining Abundances from IR Forbidden Lines

- The high temperature central engine photo-ionizes metals to forbidden upper levels that are then de-excited by electron collisions ($n_e = n_H$)
- The lines are optically thin so that the line luminosity is given by:

$$\mathbf{L_{line} = n_H n_{upper} v_e (\sigma\Delta E)_{u\mathit{l}} V_{shell}}$$

- The optically thin free-free continuum gives the hydrogen density from:

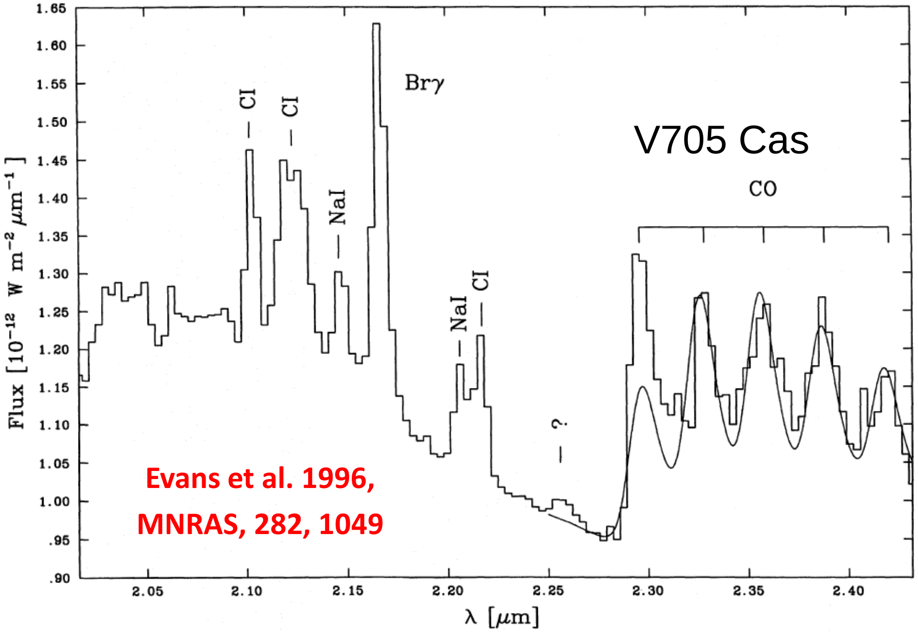
$$\mathbf{L_{free-free} = n_H^2 v_e (\sigma\Delta E)_{free-free} V_{shell}}$$

- So that the abundance for a single line is given by:

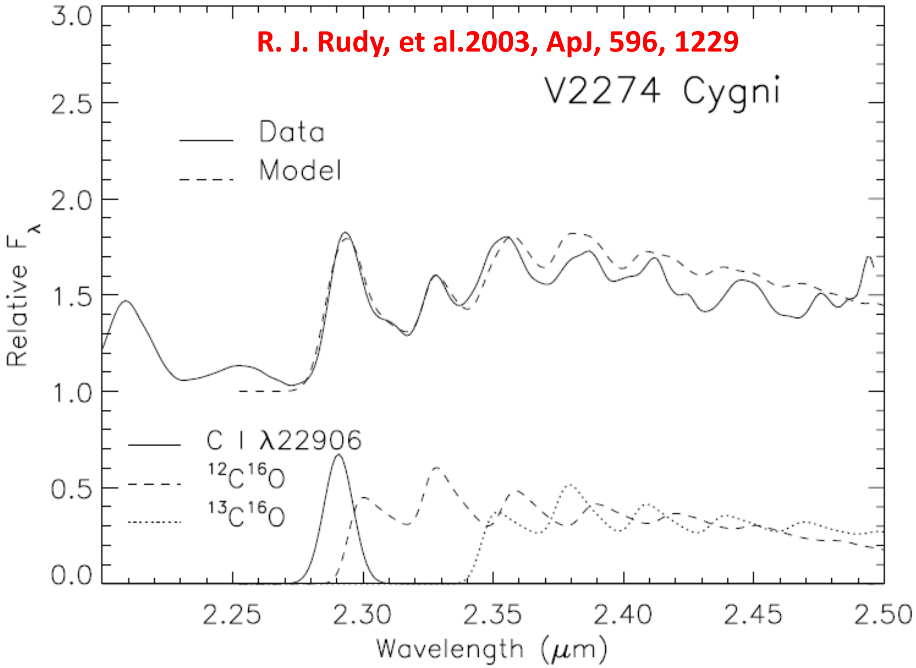
$$\mathbf{\frac{n_{upper}}{n_H} = \frac{L_{line}}{L_{free-free}} \frac{(\sigma\Delta E)_{free-free}}{(\sigma\Delta E)_{u\mathit{l}}}}$$

- A lower limit results unless all of the possible emission lines can be observed; the more lines observed, the stronger the lower limit

CO Emission in CNe and the $^{12}C/^{13}C$ Ratio



Evans et al. 1996, MNRAS, 282, 1049



R. J. Rudy, et al.2003, ApJ, 596, 1229

- CO formation has been a precursor to dust production in a number of CO novae (e.g., NQ Vul, V705 Cas, V496 Sct, and V2676 Oph)
- The $^{12}C/^{13}C$ ratio tests CN TNR models. ^{13}C was very overabundant in V2676 Oph and V2274 Cyg (factors of ~20 and ~90 respectively)

Some of the More Extreme Chemical Abundances Observed in Classical Novae from IR Data

Nova	X	Y	$\frac{(n_X/n_Y)_{nova}}{(n_X/n_Y)_\odot}$	Reference
V705 Cas	Silicates	H	≥ 17	R. D. Gehrz, et al. 1995, ApJL, 448, L119
V1974 Cyg	N	H	≈ 50	T. L. Hayward, et al. 1996, ApJ, 469, 854
V1974 Cyg	O	H	≈ 25	T. L. Hayward, et al. 1996, ApJ, 469, 854
V1974 Cyg	Ne	H	≈ 50	T. L. Hayward, et al. 1996, ApJ, 469, 854
V705 Cas	O	H	≥ 25	A. Salama, et al. 1999, MNRAS, 304, L20 (ISO)
V705 Cas	C (grains)	H	≈ 20	C. G. Mason, et al. 1998, ApJ, 494, 783
CP Cru	N	H	75	J. E. Lyke, et al. 2003, AJ, 126, 993 (ISO)
QU Vul	Ne	H	≥ 168	R. D. Gehrz, et al. 2008, ApJ, 672, 1167 (Spitzer)

Abundance Anomalies in “Neon” Novae

- ONeMg TNR’s can produce and excavate isotopes of CNO, Ne, Na, Mg, Al, Si, Ca, Ar, and S, etc. that are expelled in their ejecta
- ONeMg TNR’s are predicted to have highly enhanced ^{22}Na and ^{26}Al abundances in their outflows. These isotopes are implicated in the production of the ^{22}Ne (Ne-E) and ^{26}Mg abundance anomalies in Solar System meteoritic inclusions:

^{22}Ne via: $^{22}\mathrm{Na} \rightarrow {}^{22}\mathrm{Ne} + e^{+} + \nu \quad (\tau_{1/2} = 2.7\ \mathrm{yr})^{*}$

^{26}Mg via: $^{26}\mathrm{Al} \rightarrow {}^{26}\mathrm{Mg} + e^{+} + \nu \quad (\tau_{1/2} = 7\times10^{5}\ \mathrm{yr})$

*Note that IR lines of [Na III] 7.32μm, [Na IV] 9.04 μm, 21.29 μm, [Na VI] 8.61 μm, 14.33 μm, and [Na VIII] 6.23 μm, 13.66 μm are predicted to occur but have never yet been detected

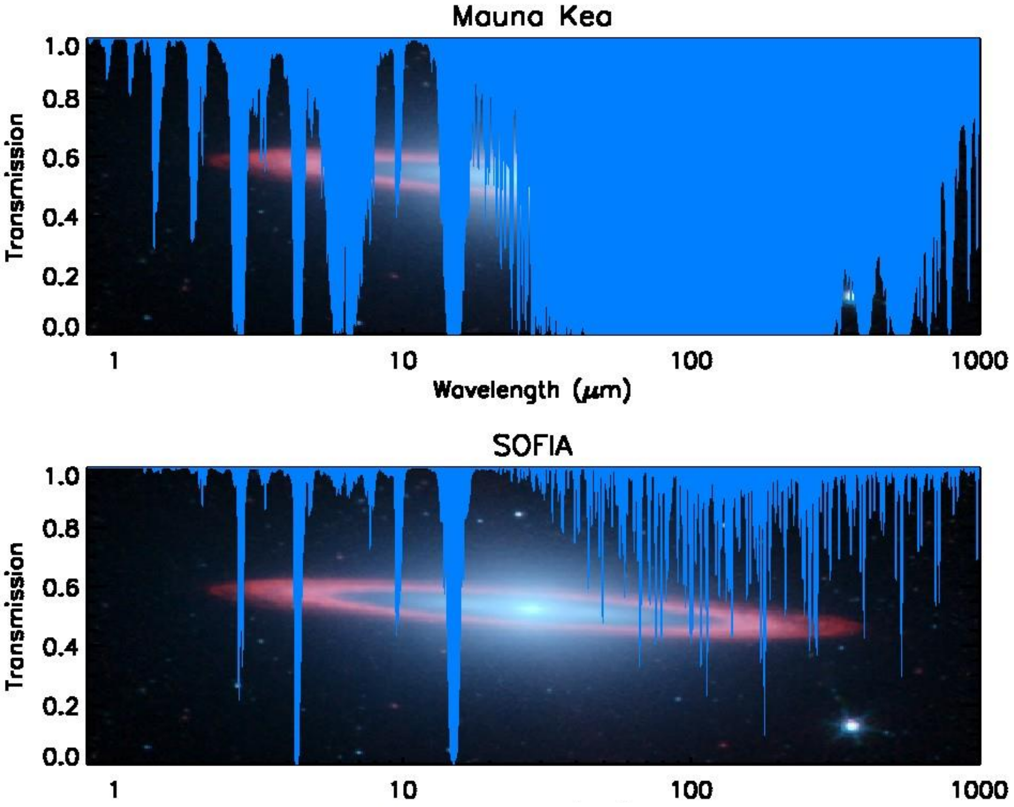
Nova Research in the Infrared with SOFIA

The NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA) Clipper Lindbergh

- 2.5-m clear aperture airborne telescope flying at 45,000 feet altitude
- 0.3 – 240 μm with spectral resolutions from $R = \lambda/\Delta\lambda = 200$ to 3,000
- Covers all wavelengths and spectral resolutions needed to study nova dust mineralogy and abundances from IR forbidden emission lines

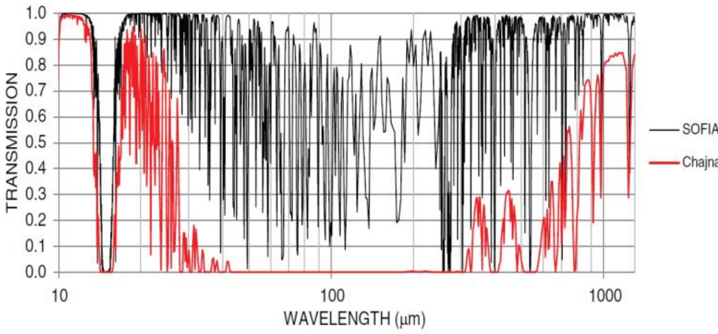
The SOFIA Observing Environment

- **Above 99.8% of the water vapor**
- **Transmission at 14 km >80% from 1 to 800 µm**
- **Emphasis is on the obscured IR regions from 30 to 300 µm**



SOFIA , 10µm Precipitable Water Vapor

Cerro Chajnantor, 700µm Precipitable Water Vapor

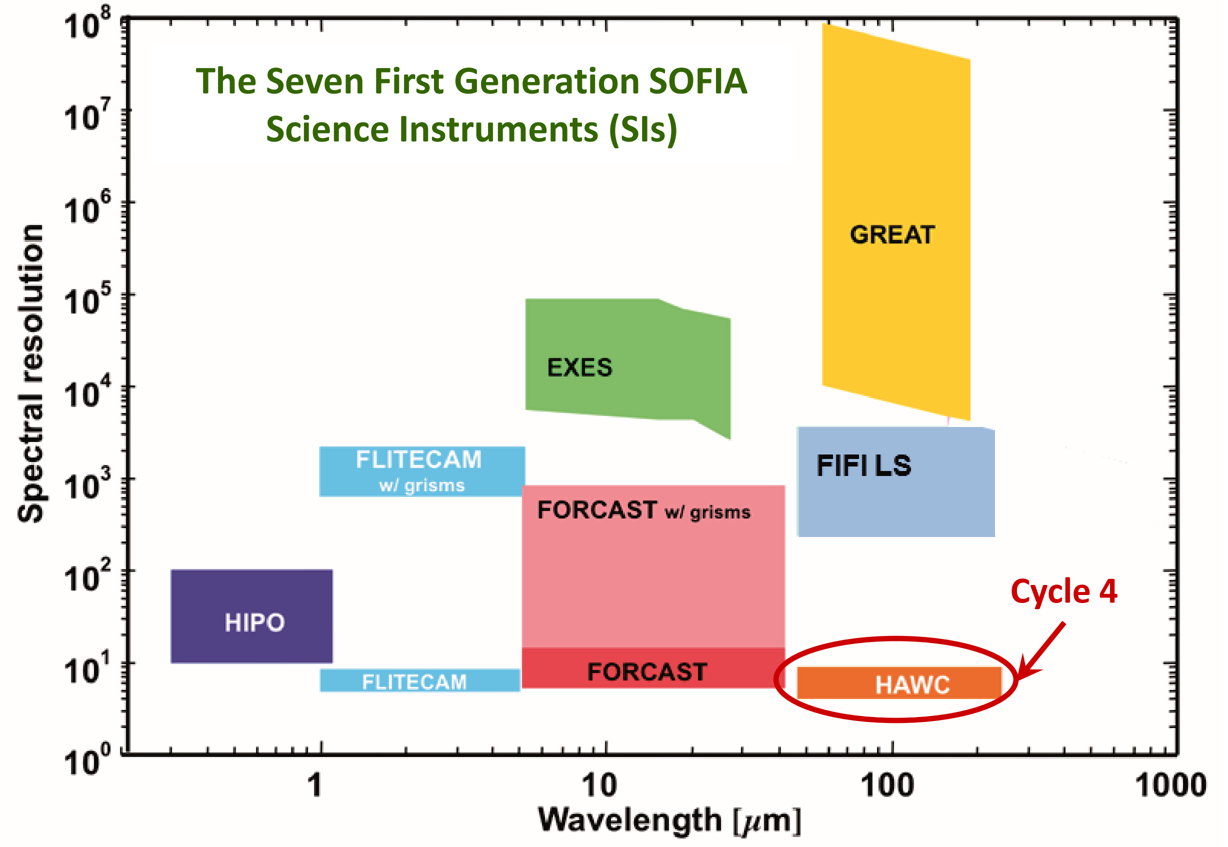


E.T Young et al. 2012, ApJ, 749, L17

SOFIA Science Instruments

SOFIA supports a unique, expandable suite of Science Instruments (SIs)

- SIs cover the full IR range with imagers and low to high resolution spectrographs
- SOFIA will take advantage of improvements in instrument technology.
- Will support both Facility Instruments and PI Class Instruments



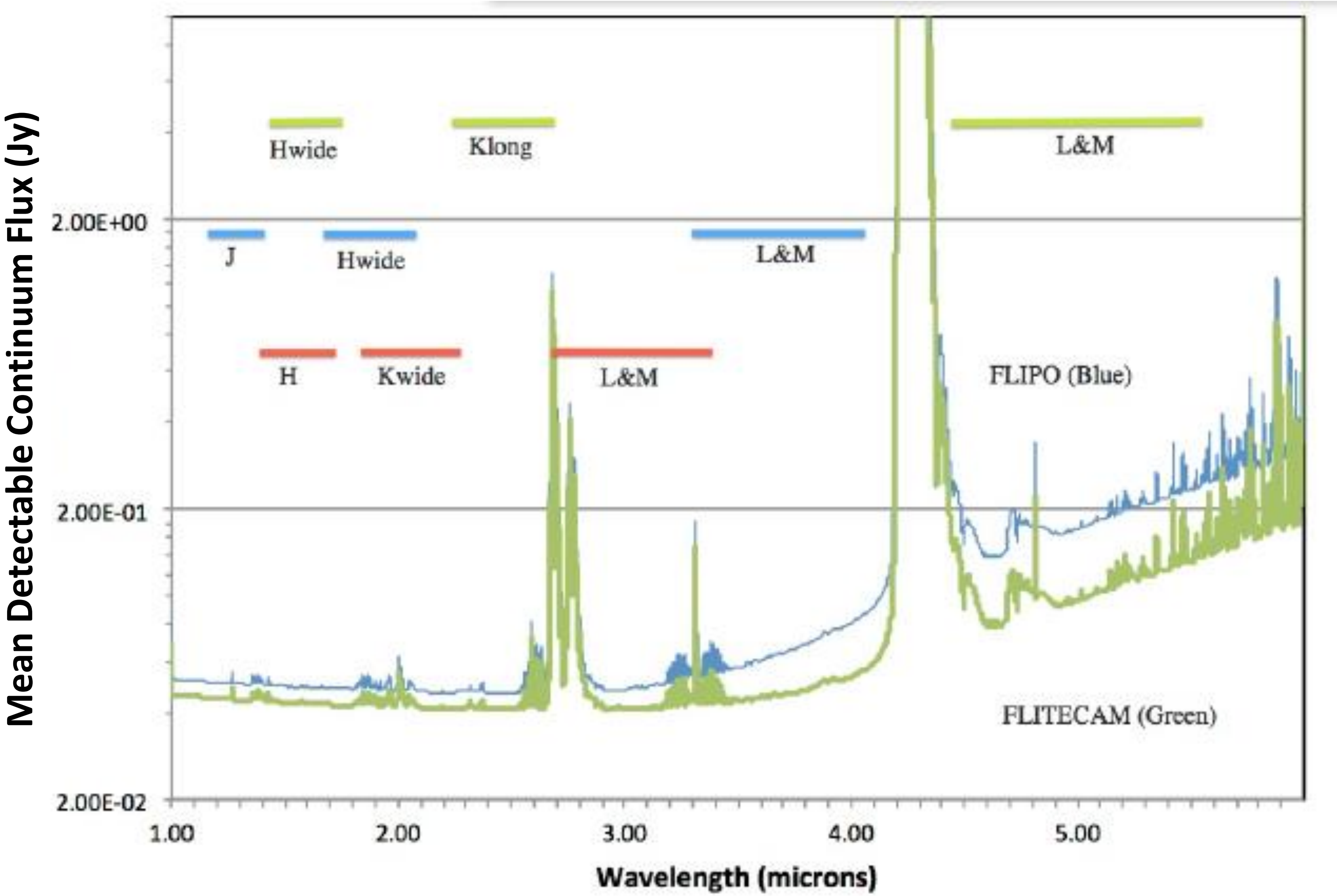
Minnesota Institute for Astrophysics, January 29, 2016

First Science Results with FORCAST

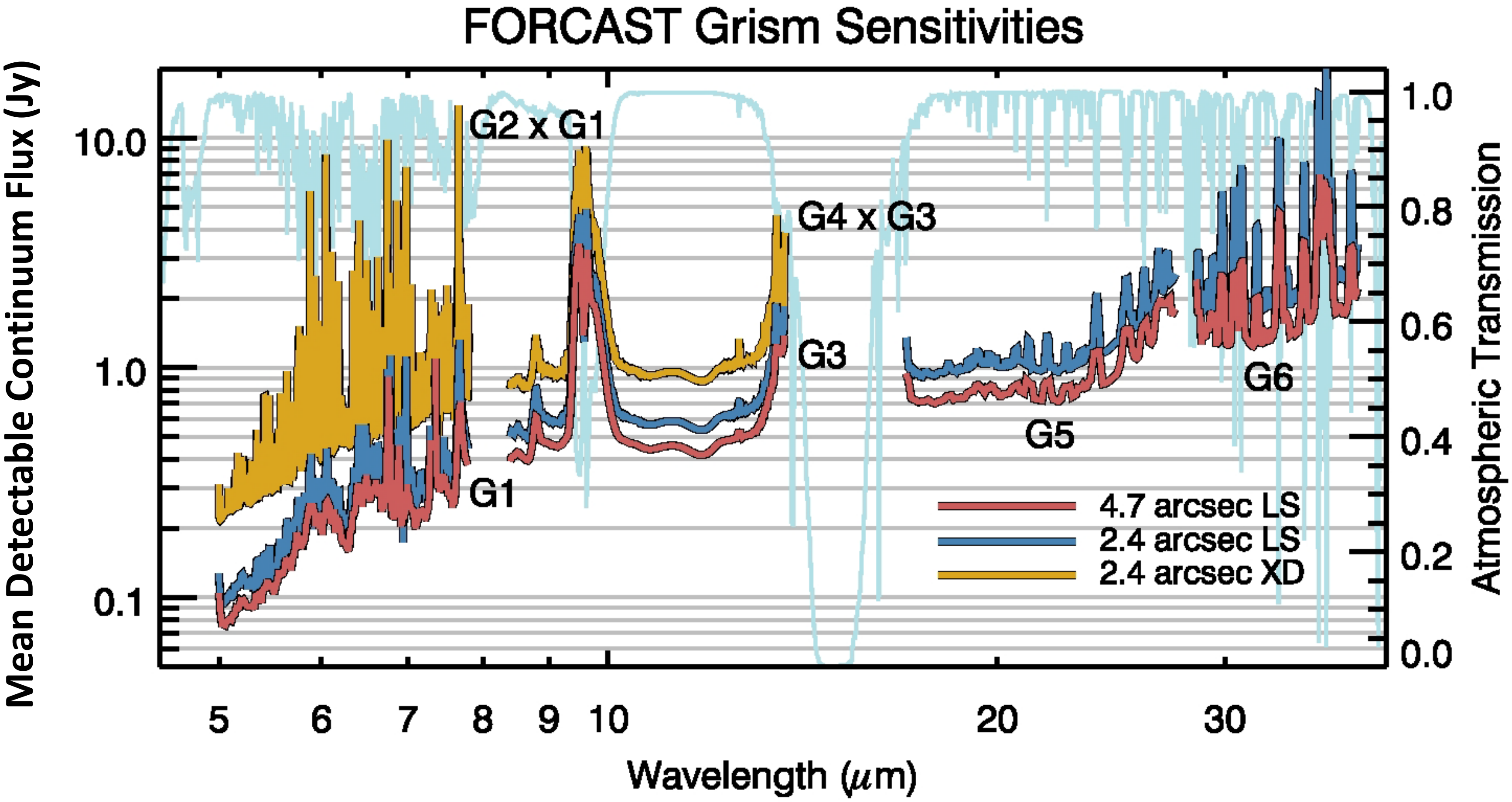
The FORCAST Team

The DSI Telescope Assembly and Mission Operations Team in action during the First Light Flight

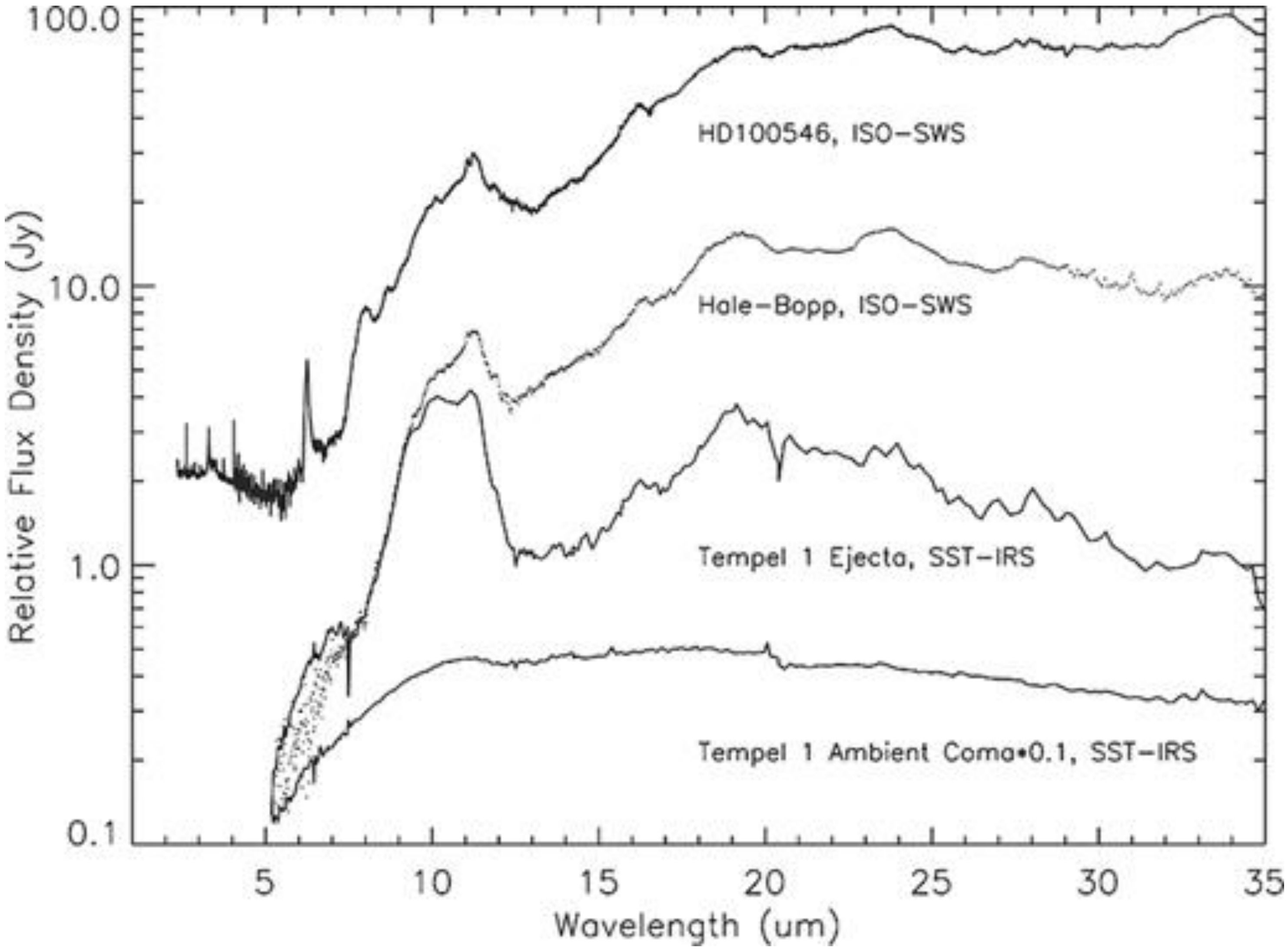
Spectroscopy with FLITECAM Grisms



Spectroscopy with FORCAST Grisms



Dust Mineralogy with FORCAST Grisms



ASTRO
2001,

Twenty-Eight Selected Infrared Forbidden Lines with $\lambda_o > 5\mu m$ within the SOFIA FORCAST GRISM Passbands

SPECIES	λ_O (μM)	SPECIES	λ_O (μM)	SPECIES	λ_O (μM)	SPECIES	λ_O (μM)
[O IV]	25.91	[Na VIII]*	6.23	[Al X]	6.06	[Mg V]	13.54
[O V]	32.61	[Na III]*	7.32	[Al VI]	9.12	[Si VII]	6.51
[Ne VI]	7.64	[Na VI]*	8.61	[Al VII]	37.6	[Si VIII]	18.45
[Ne II]	12.81	[Na IV]*	9.04	[Mg VII]	5.50	[Si II]	34.81
[Ne VII]	22.0	[Na VIII]*	13.66	[Mg V]	5.60	[S IV]	10.51
[Ne V]	24.28	[Na IV]*	21.29	[Mg IX]	8.87	[S V]	27.10
[Ne III]	36.02	[Al VIII]	5.85	[Mg VII]	9.03	[S III]	33.47

*The Na lines, predicted to result from the production of ^{22}Na in the TNR, have not yet been detected

The SOFIA Target of Opportunity Nova Team

- **PI: R. D. Gehrz, University of Minnesota**
- **Co-I's:**

A. Evans, University of Keele

Charles E. Woodward and D. Shenoy, University of Minnesota

N. M. Ashok and D. P. K. Banerjee, Mt. Abu Observatory

S. Eyres and M. Rushton, University of Central Lancashire

L. A. Helton, USRA/SOFIA

L. Keller, Ithaca College

Joachim Krautter, Landessternwarte Heidelberg

T. Liimets, University of Tartu

S. S. Mohamed, South African Astronomical Observatory

G. Schwarz, American Astronomical Society

S. G. Starrfield, Arizona State University

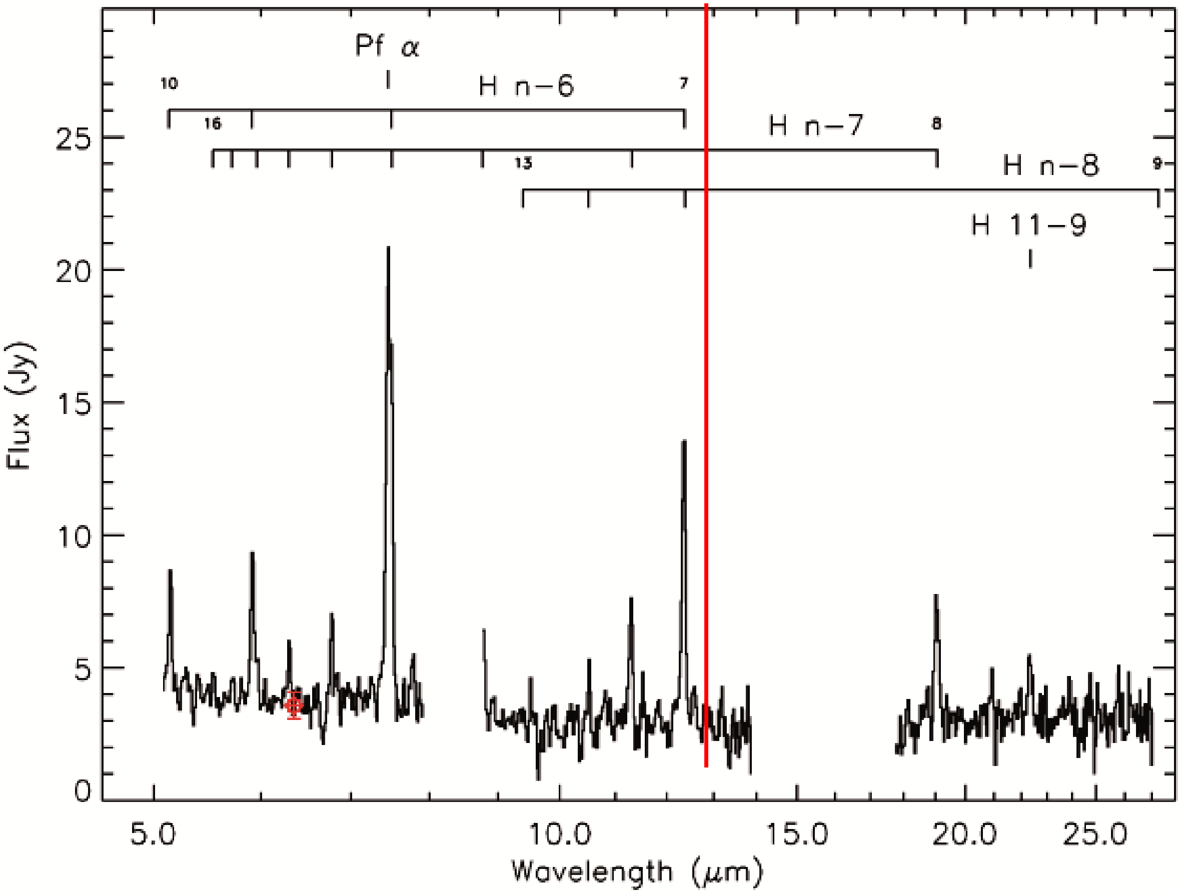
R. M. Wagner, Large Binocular Telescope Observatory

"Physics of Evolved Stars 2015", Nice, France, 2015 June 09 11/03/03

Current and Future SOFIA Nova Programs

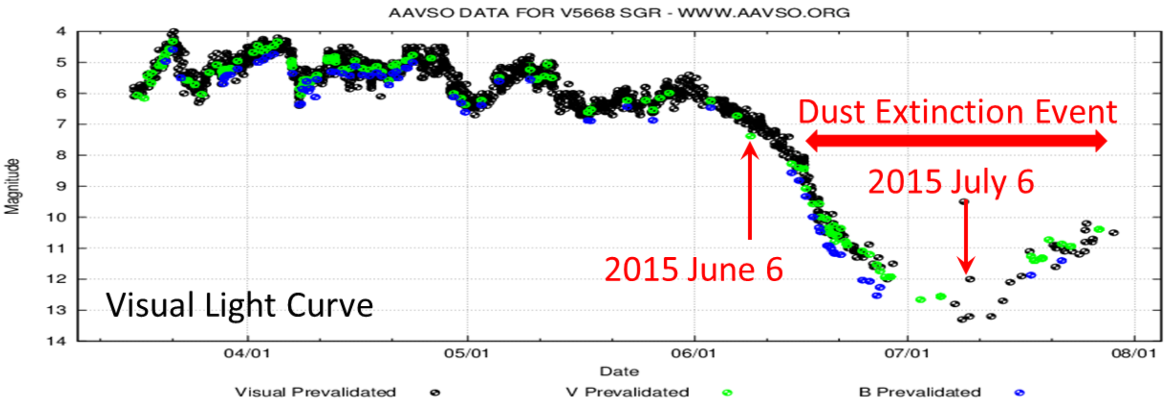
- **Past and Current SOFIA Nova Programs (38 hours)**
  - R. D. Gehrz et al.: “Target of Opportunity observations of Classical Novae with SOFIA”, 20 target-time hours over Cycles 1, 2, 3, and 4
  - L. A. Helton et al.: “An Examination of Dust Formation and Destruction in the Classical Nova V1280 Sco”, 3 target-time hours during Cycle 1
  - L. A. Helton et al.: “A FORCAST Study of the Classical Nova V1369 Cen (Nova Centauri 2013)”, 7 target-time hours during Cycle 3
  - L. A. Helton et al.: “An Examination of Dust Formation and Evolution in the Ejecta of Nova Sagittarii 2015 No. 2”, 8 target-time hours during Cycle 4
- **Future SOFIA Observations**
  - The SOFIA Program Announces Observing Opportunities on an annual basis
  - The US queue (80% of the observing time) is open on an international basis
  - The German queue (20% of the observing time) is only open to Germans
  - The Cycle 5 call will be issued on May 1, 2016. The observing period will be from February 1, 2017 through January 31, 2018

First Results: SOFIA FORCAST Grism Spectrum of V339 Del



- Pure Hydrogen emission spectrum
- Metallic forbidden lines are quenched at the high shell density of ~10^{11} cm^{-3}

SOFIA FORCAST Grism Spectra of Nova Sgr 2015#2

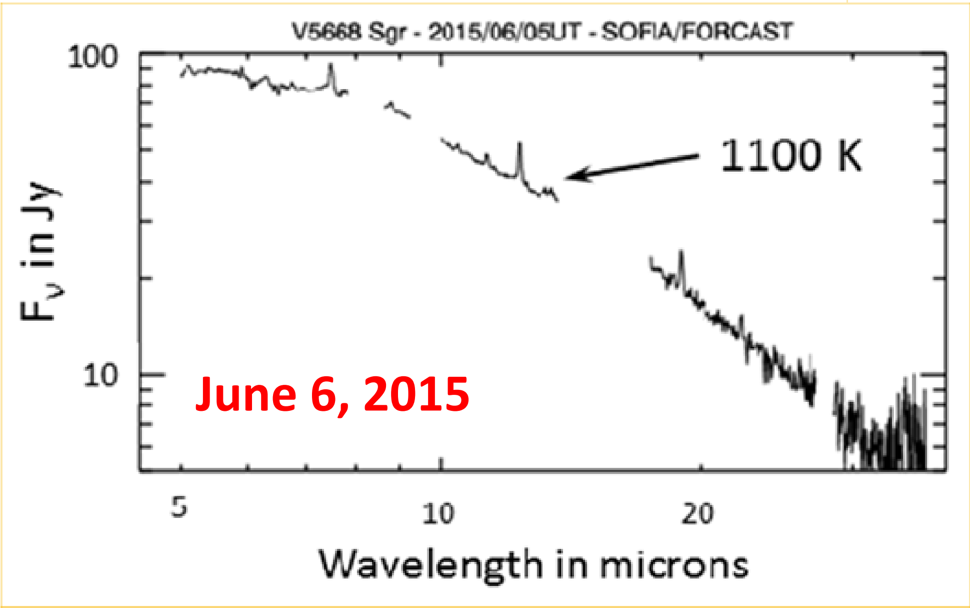


Dust Extinction Event

2015 July 6

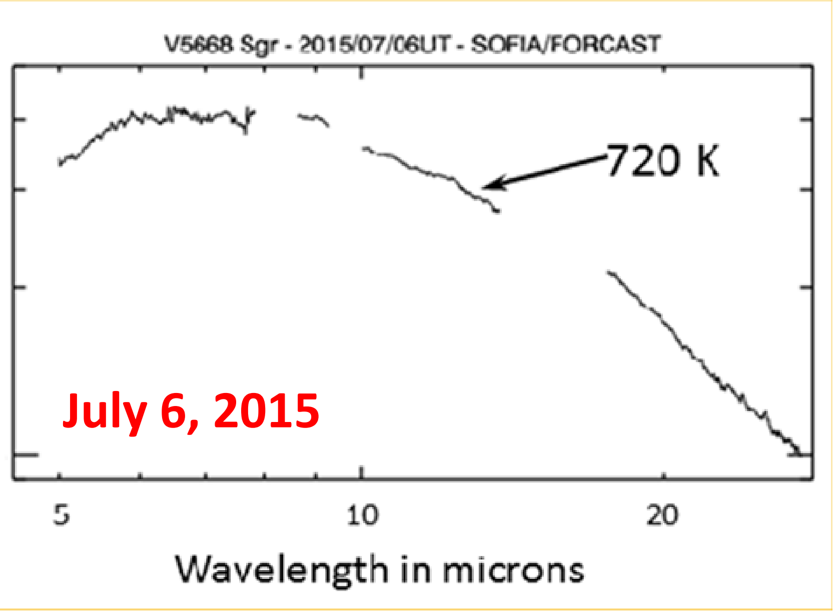
2015 June 6

Visual Light Curve



1100 K

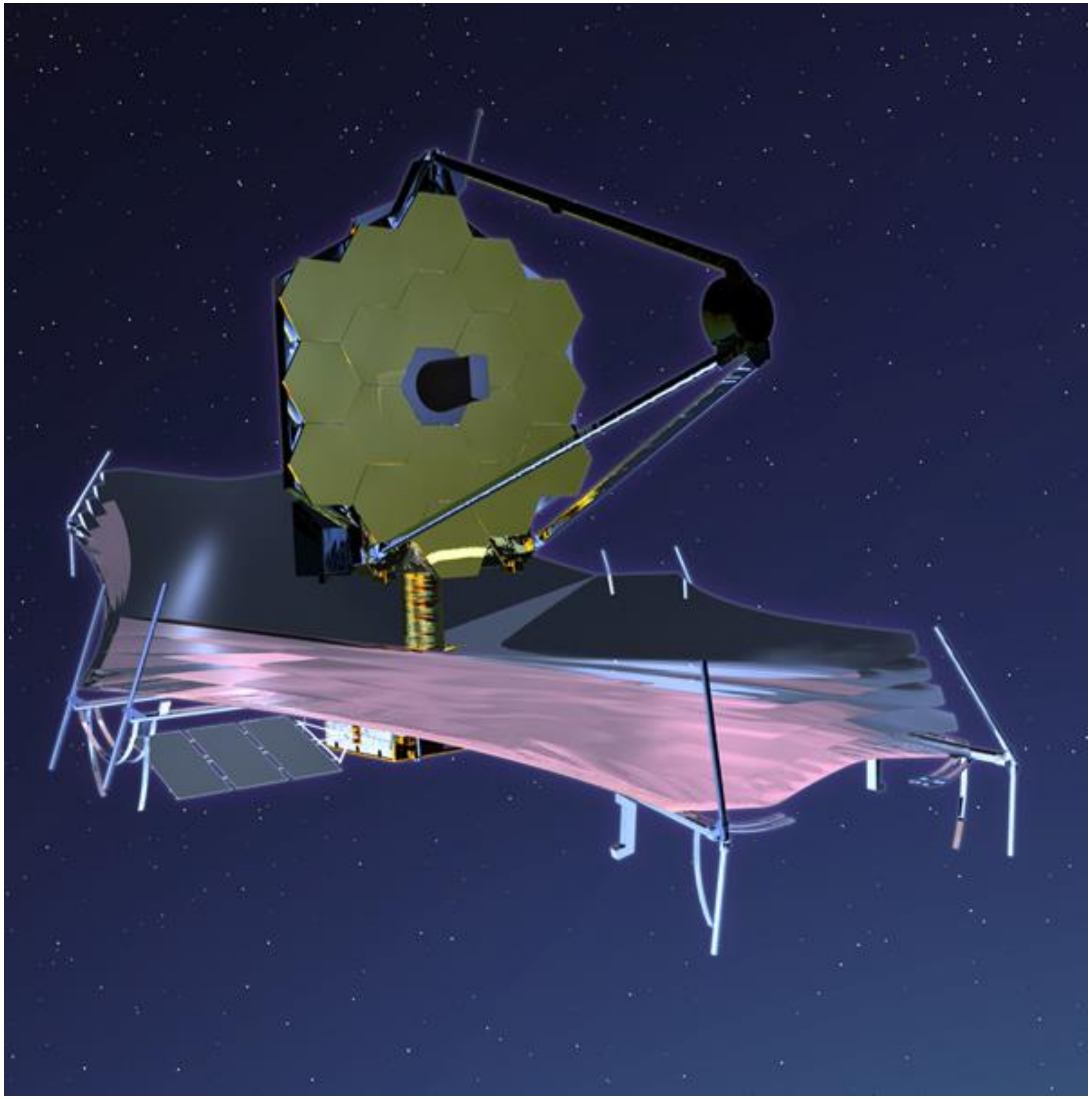
June 6, 2015



720 K

July 6, 2015

IMAGING AND SPECTROSCOPY OF CN SHELLS WITH JWST



- 0.6 – 28 µm
- T ~ 40 K
- Spectrometers and imagers
- 6.5-m aperture (25 m^2)
- Flies at L_2
- October 2018 Launch
- Five-ten year lifetime

The JWST Center of Curvature Optical Test

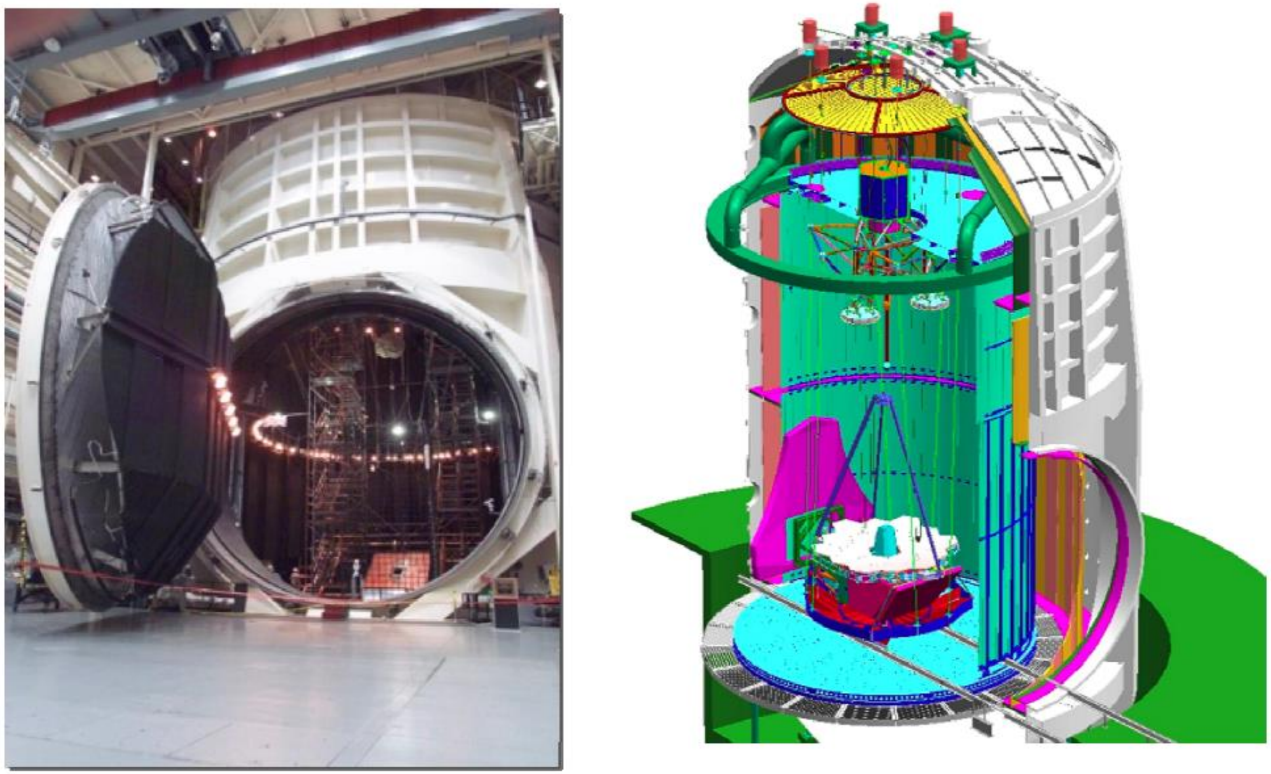
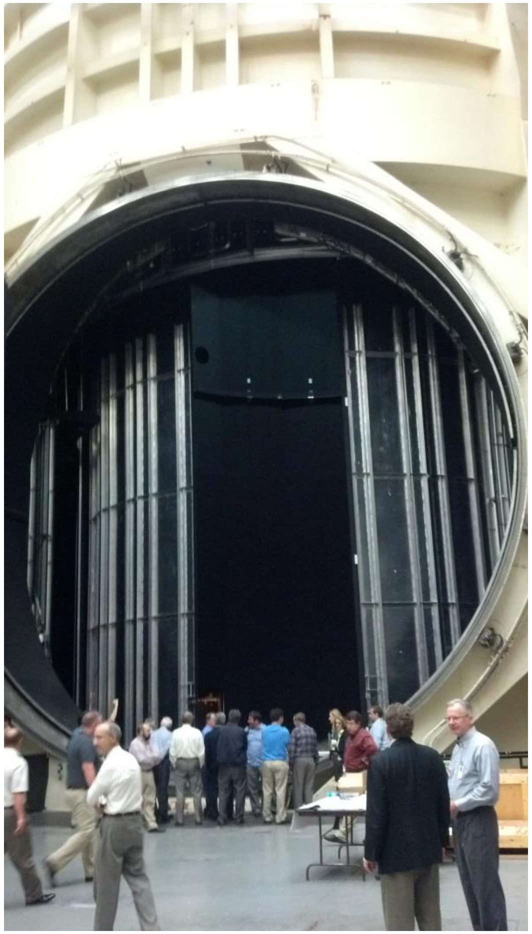
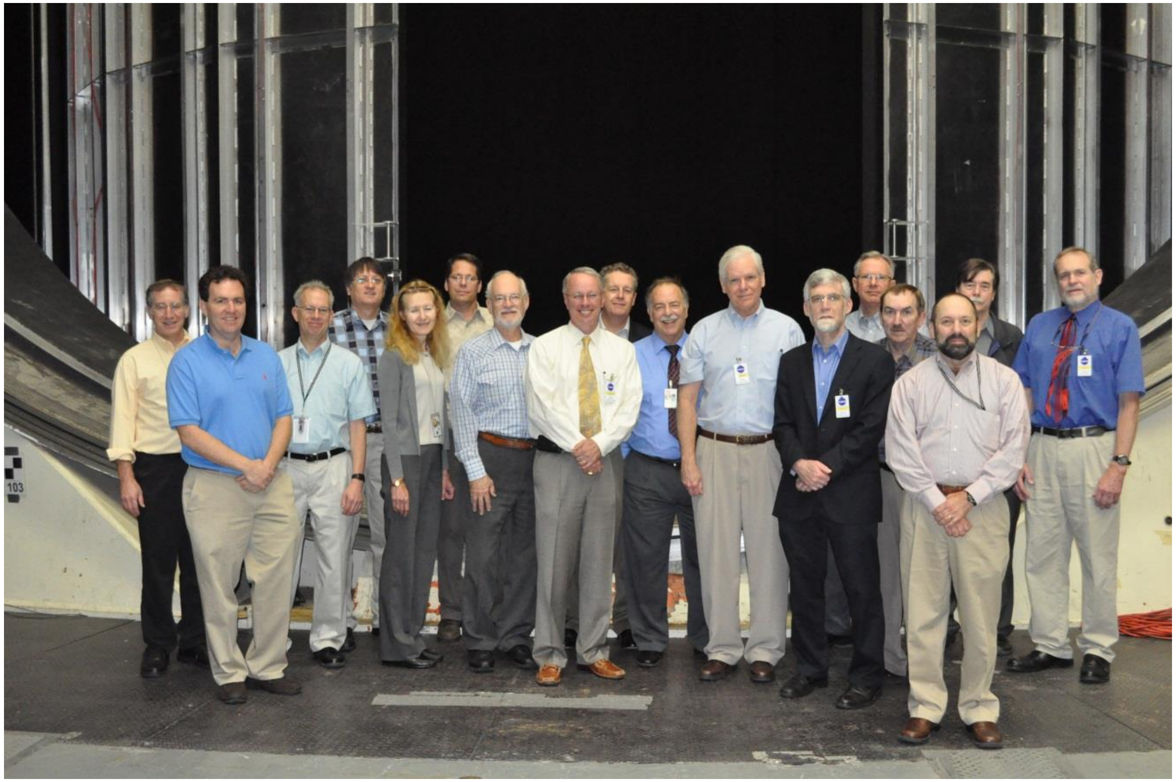


Fig. 8. On the left is shown the Johnson Space Flight Center's Chamber A. On the right is shown the configuration in which the optical testing of JWST will be undertaken in Chamber A.





The JWST Product Integrity Team (PIT) Inspects JSFC Chamber A on October 8, 2012

JWST STATUS: ASSEMBLY AT GSFC ON 1/15/2016

Summary and Conclusions

- SOFIA FLITECAM and FORCAST grisms cover the entire IR spectral range where metallic forbidden lines and dust emission features occur
- SOFIA will see many lines and dust features that cannot be observed from the ground
- The spectral resolution is appropriate for determining abundances and mineralogy
- SOFIA can fly anywhere and any time to respond to transient events
- No existing or planned space observatory can compete in terms of either spectral coverage or timely response (JWST only goes to 28 µm and has severe viewing constraints)