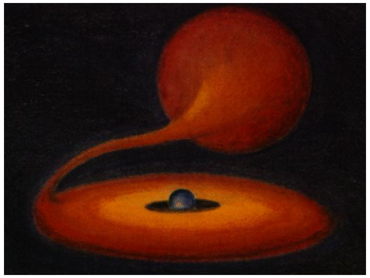
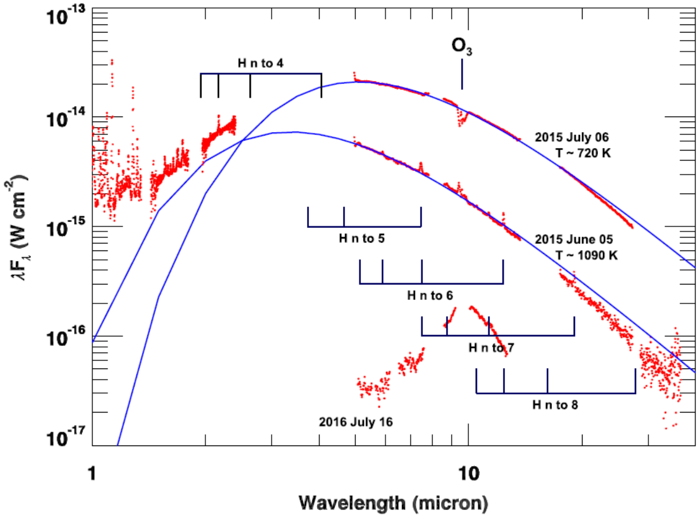
Infrared Observations of Novae in the SOFIA Era: Update





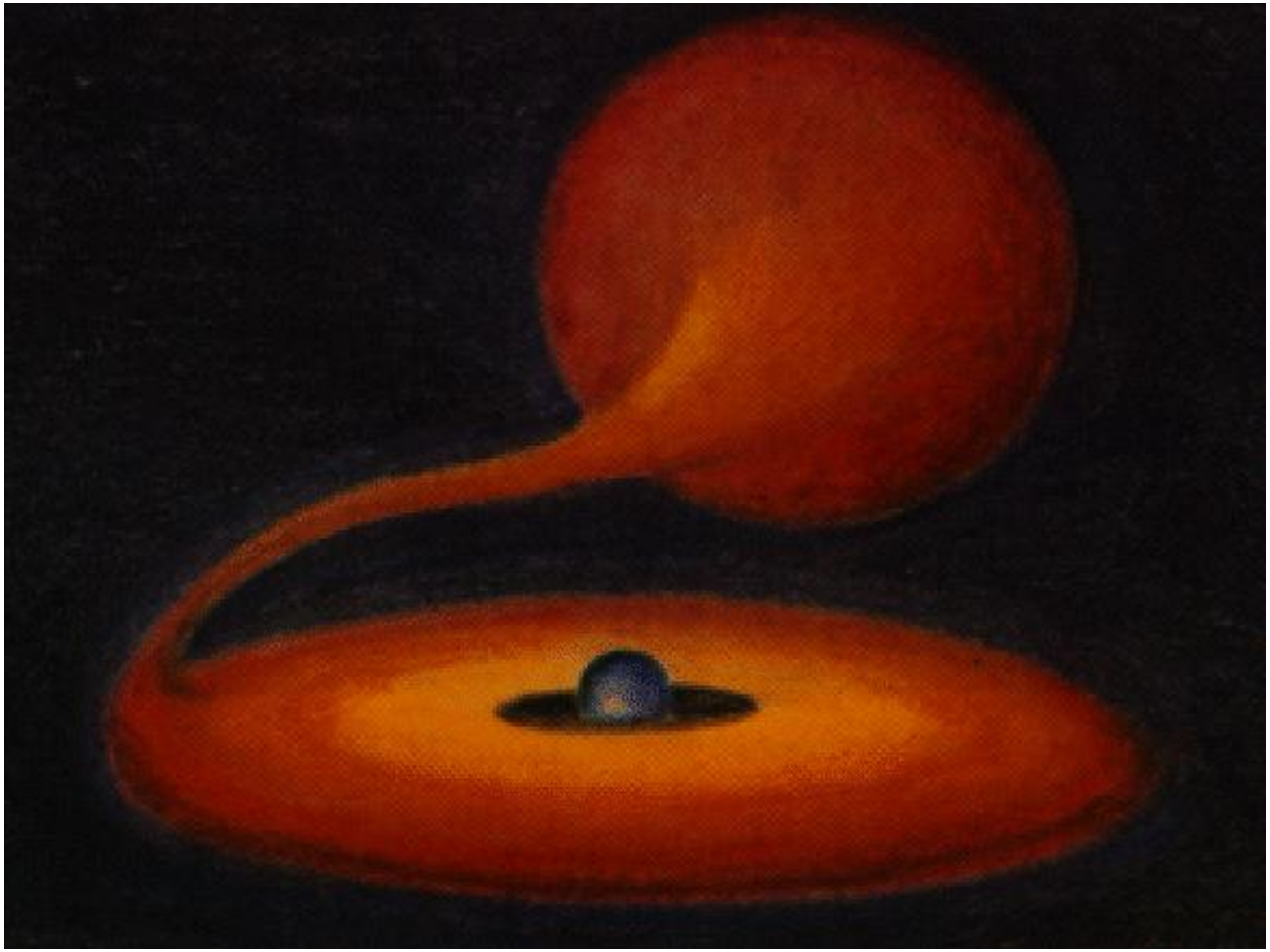
R. D. Gehrz

Minnesota Institute for Astrophysics, University of Minnesota, USA

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 JWST
- Summary

Nova Explosion: Accretion from a secondary star onto a WD primary initiates a thermonuclear runaway (TNR)

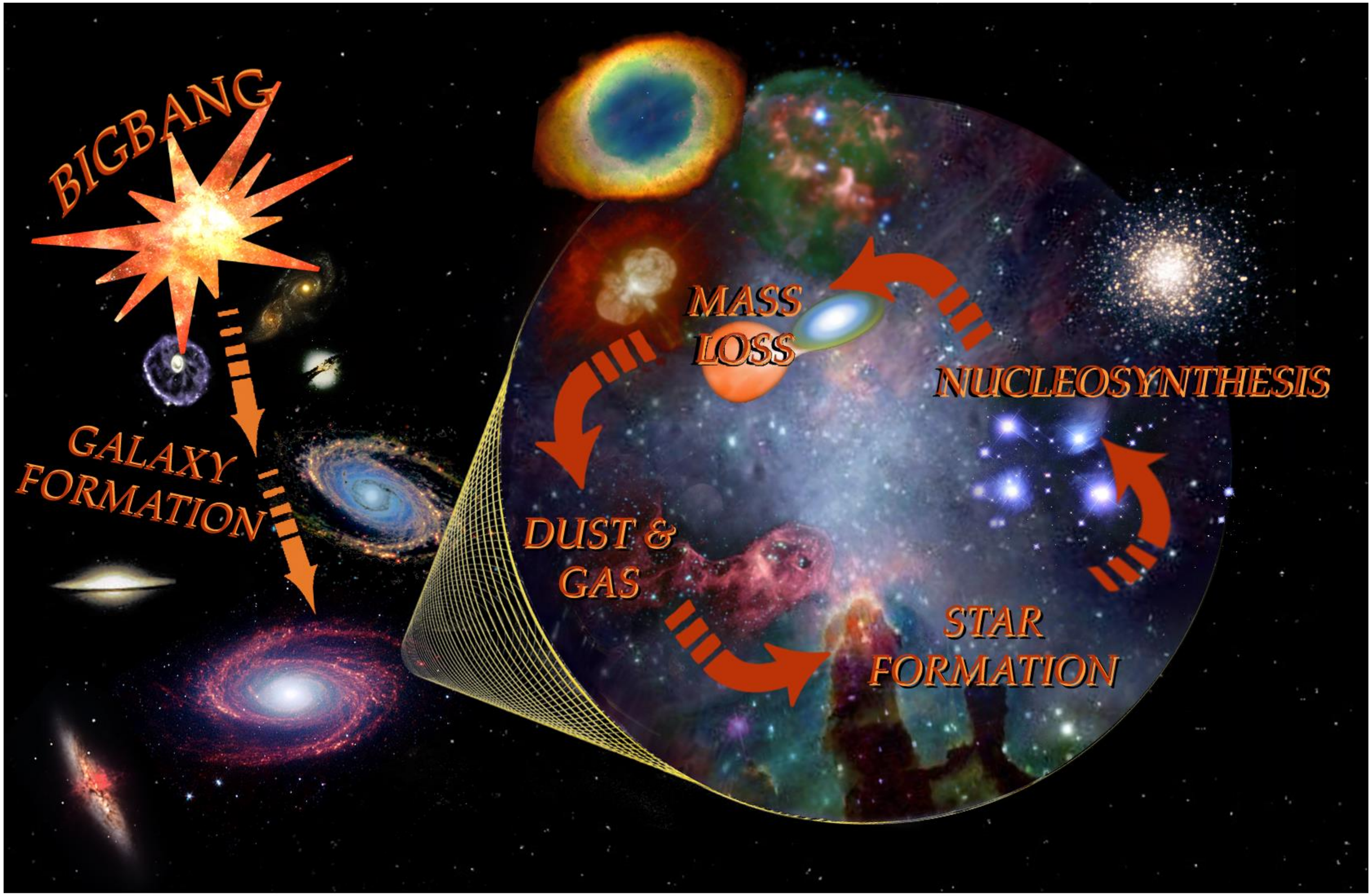


The Astrophysical Importance of Novae

- They inject gas phase and solid phase materials into the ISM that become incorporated into new stellar and planetary systems

- They are ideal laboratories for studying the formation and growth of astrophysical mineral grains of all types

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 $\mathrm{yr^{-1}}$: $[dM/dt]_{\mathrm{CNe}} \approx 7\mathrm{x}10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$**
- **0.01 - 0.02 $\mathrm{yr^{-1}}$: $[dM/dt]_{\mathrm{SNe}} \approx 6\mathrm{x}10^{-2}\ M_\odot\ \mathrm{yr}^{-1}$**

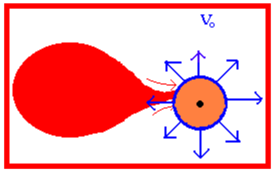
Conclusion: CNe may be important on a global Galactic scale if they produce isotopic abundances that are ≥ 10 times SN abundances and ≥ 100 times Solar abundances

**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)*

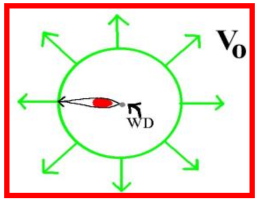
How the IR Shows what Nova Explosions Make

New elements are synthesized in the explosion

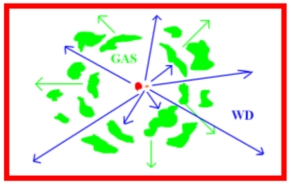
The ejected material is expelled into the ISM and incorporated into new stellar and planetary systems



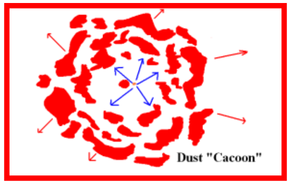
Fireball expansion phase



Free-free emission phase

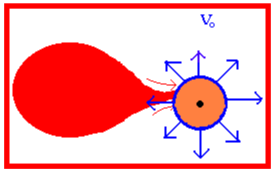


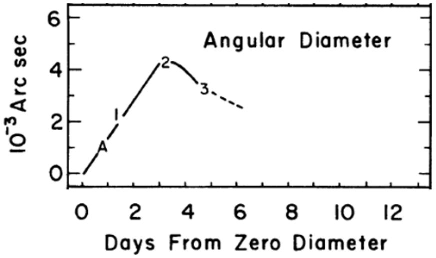
IR line emission from gas



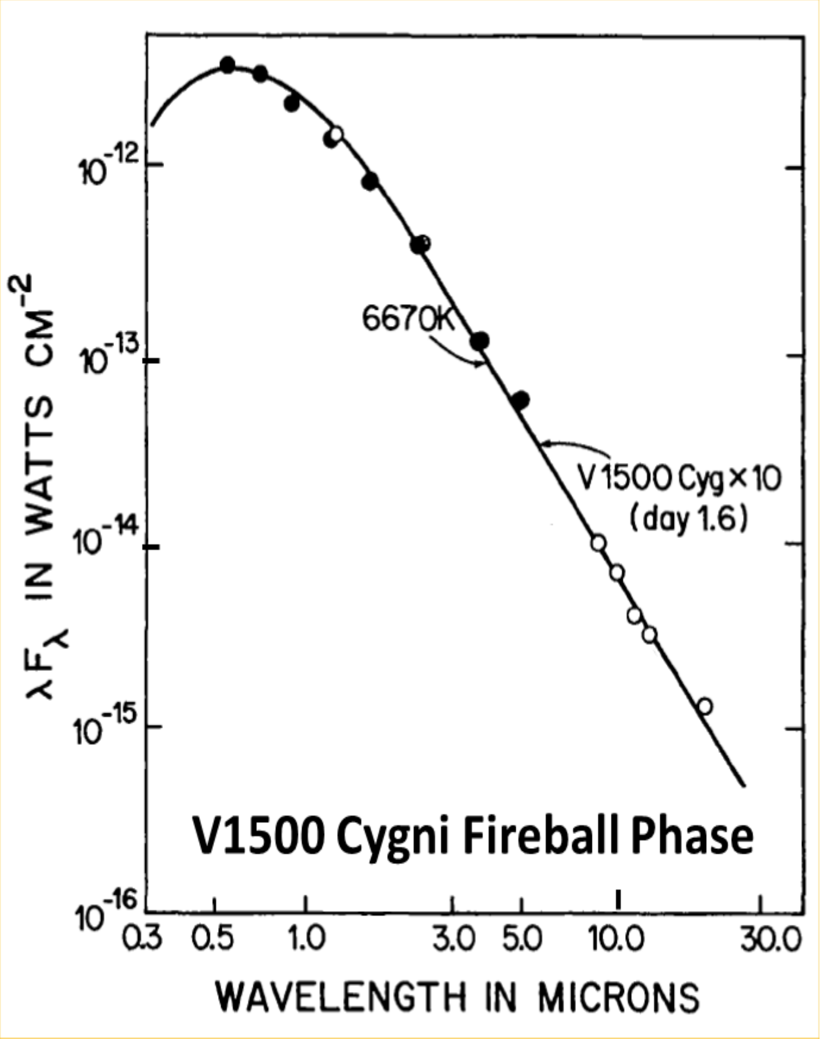
IR thermal emission from dust

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:**

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

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

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

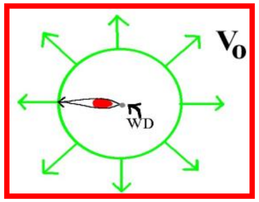
Parameters Measured by IR Observations give the Blackbody Angular Radius

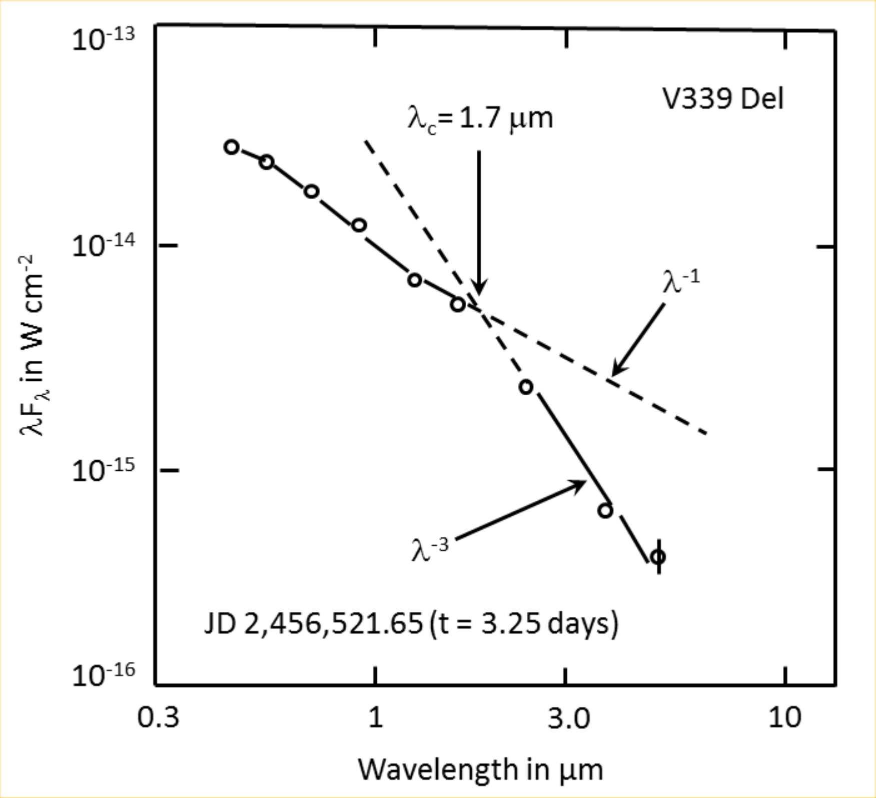
- $f = (1.36[\lambda F_\lambda]_{max})$ is the apparent flux of the SED, T_{BB} is the blackbody temperature of the SED, D is the distance to the nova, V_o is the outflow velocity, and $R = V_o t$ is the radius of the ejected shell at time t after the explosion

- $L = 4\pi D^2 f = 4\pi R^2 \sigma T_{BB}^{\ 4}$

- So the angular radius is $\theta_{BB} = \frac{R}{D} = \left[\frac{f}{\sigma T_{BB}^{\ 4}}\right]^{1/2}$

The SED During the Free-Free Expansion Phase Gives the Hydrogen Number Density and the Ejected Mass

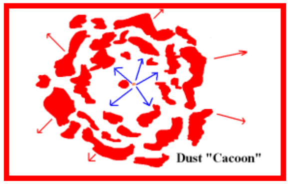


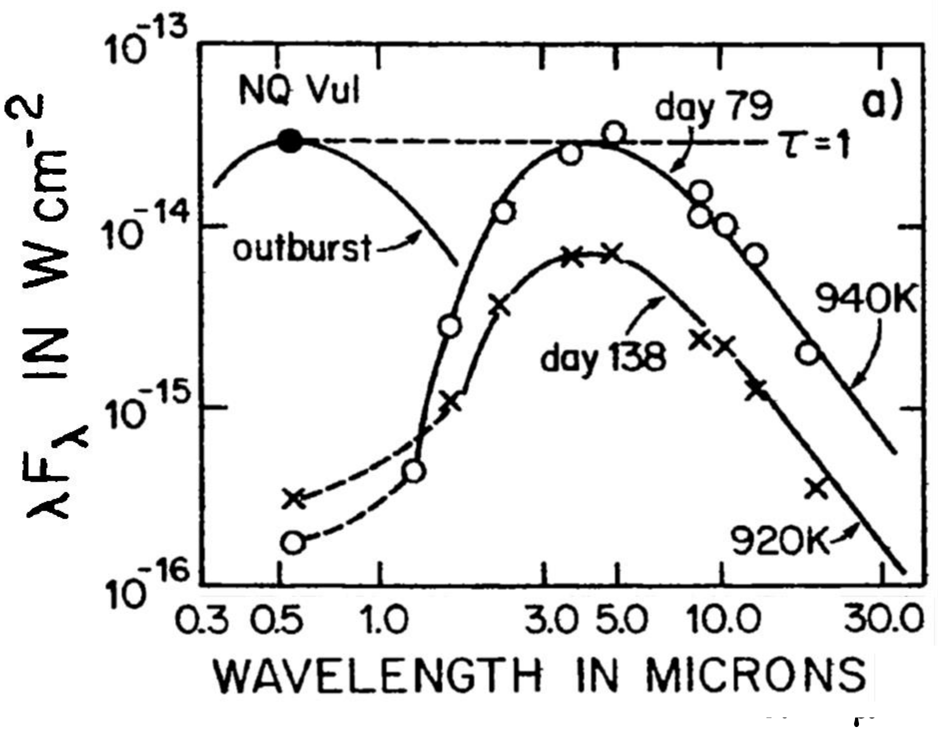


R. D. Gehrz, et al. 2015, ApJ, 812, 132

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

The Dust Formation Phase



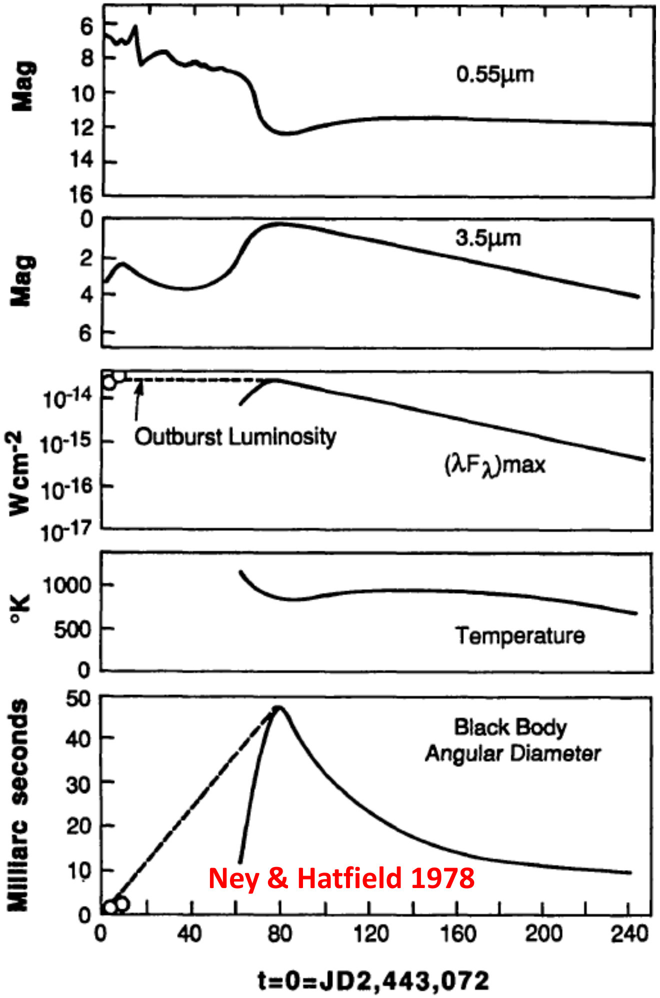


R. D. Gehrz (1988)

- 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

The Signature of Dust Condensation in CO Novae

NQ Vul



Ney & Hatfield 1978

$$L_o \approx L_{Eddington}$$

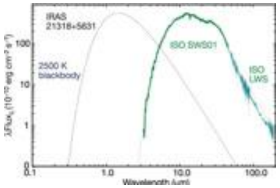
$$T_c \approx 1000\ K$$

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

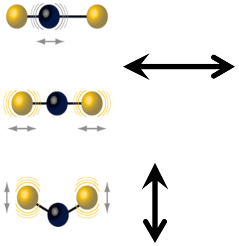
$$t_C \approx \frac{R_C}{V_O}$$

Infrared Spectra of Astrophysical Dust Grains

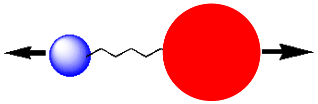
- Carbon and iron: Smooth emissivity



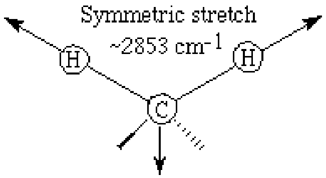
- Silicates: SiO_2 bond stretching and bending vibrational mode emission at 10 μm and 20 μm

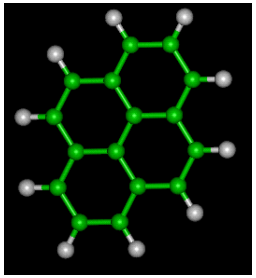


- Silicon Carbide: SiC stretching vibrational mode emission at 11.3 μm



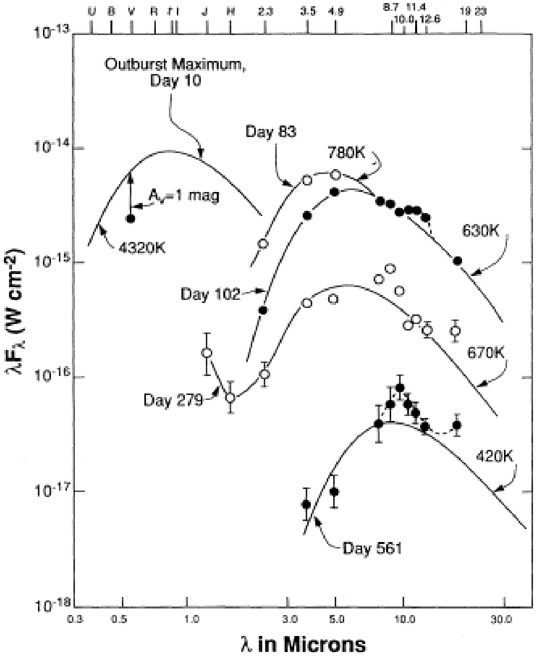
- Hydrocarbons (HAC and PAH): C-H stretching and bending at 3.3 μm, C-C stretching modes at 6 - 18 μm, drumhead modes at longer wavelengths

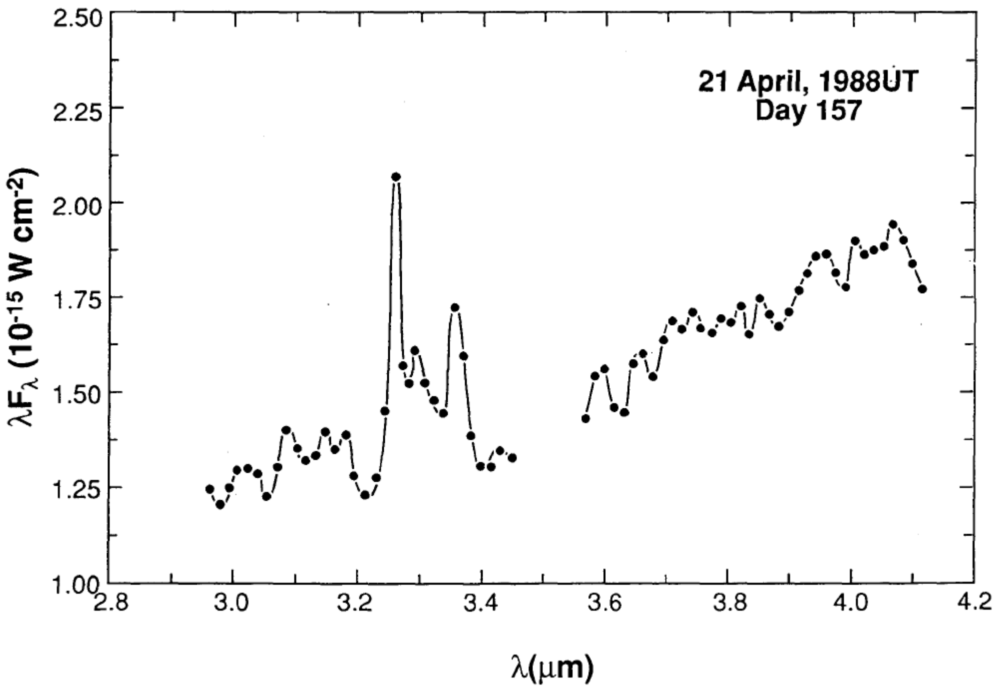




Multiple Grain Compositions in a Single Nova: QV Vul

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



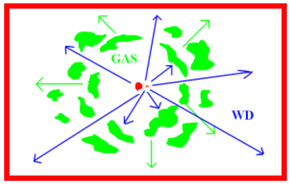


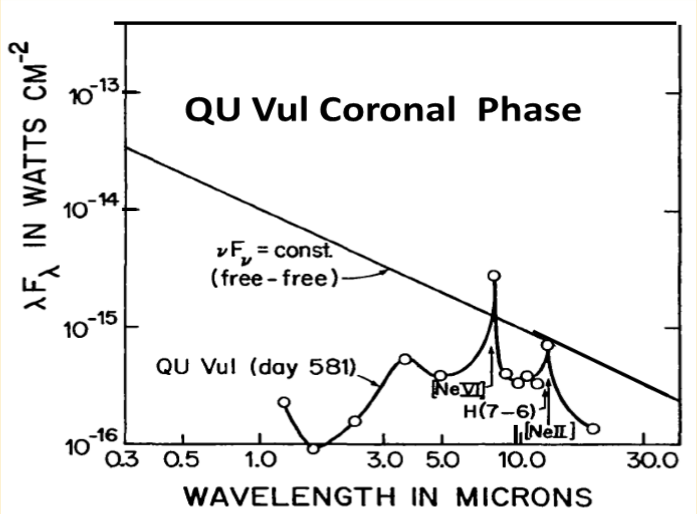
- **Carbon, Silicates, SiC, and PAH grains formed at different epochs in QV Vul suggesting abundance gradients in the ejecta.**
- **A. D. Scott (2000, MNRAS, 313, 775-782) has shown that this could be explained by an asymmetric ejection due to a TNR on a rotating WD**

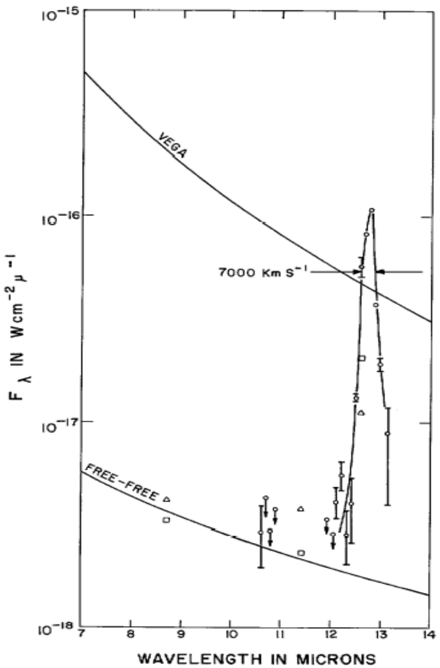
Summary of What is Known About Nova Dust

- A small fraction (~20 - 30%) of classical novae form dust
- Novae produce carbon, SiC, silicates, and hydrocarbons
- Nova 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
- The abundance of condensed material is given by the dust to gas ratio, M_{dust}/M_{gas}

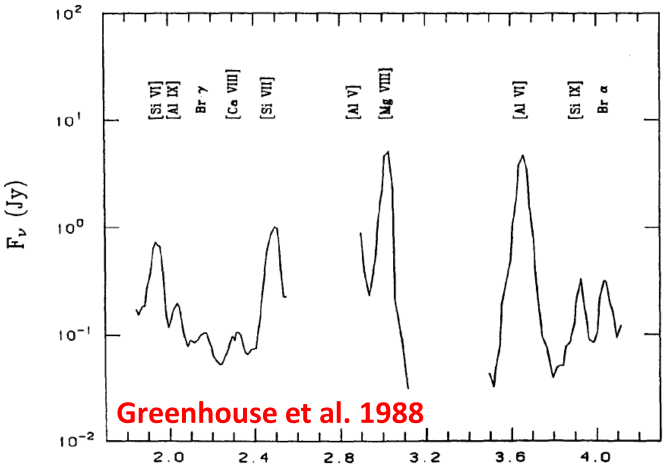
IR Forbidden Line Emission in Novae







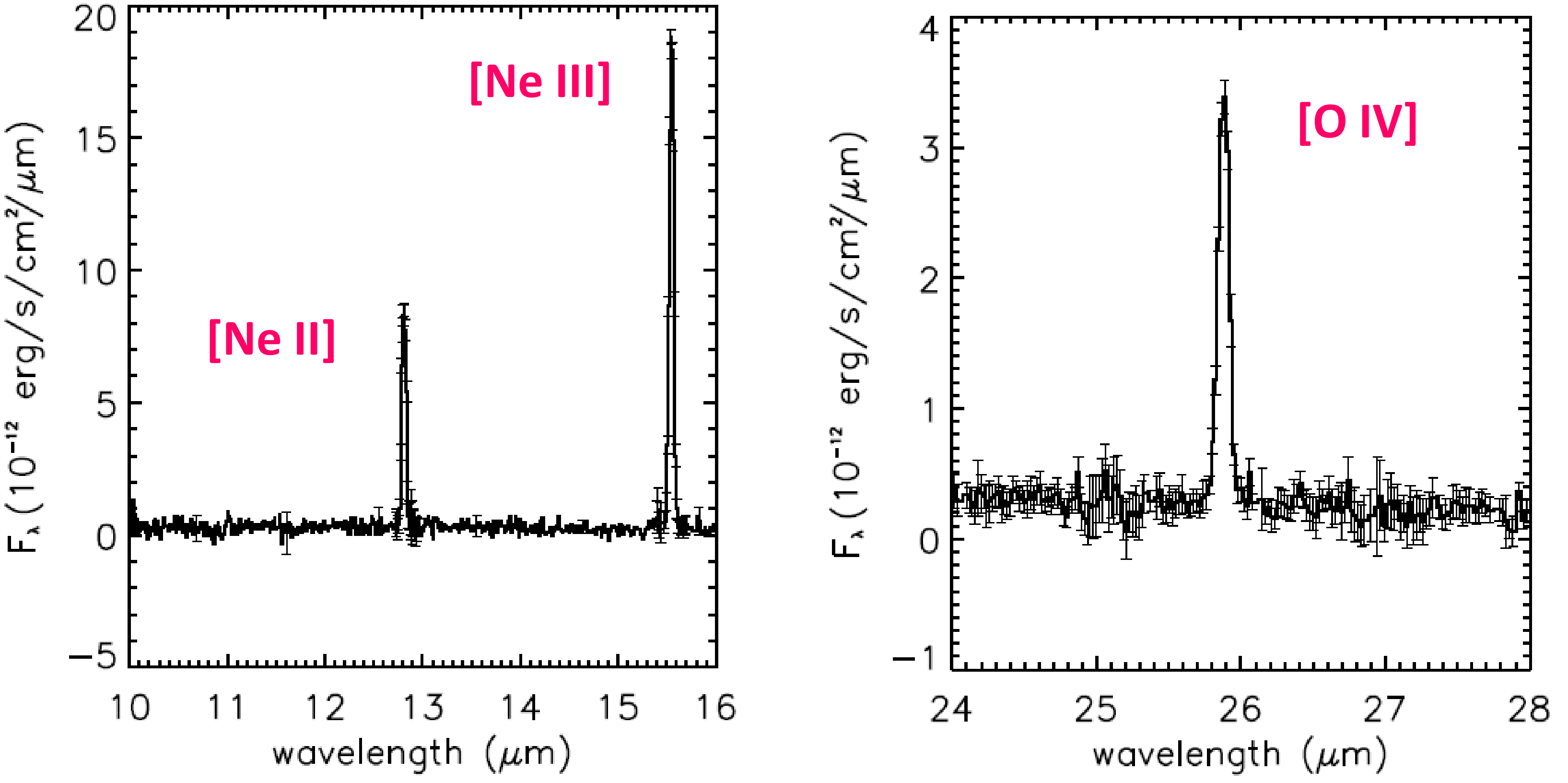
Gehrz et al. 1985



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

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:

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

- 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:

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

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

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

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

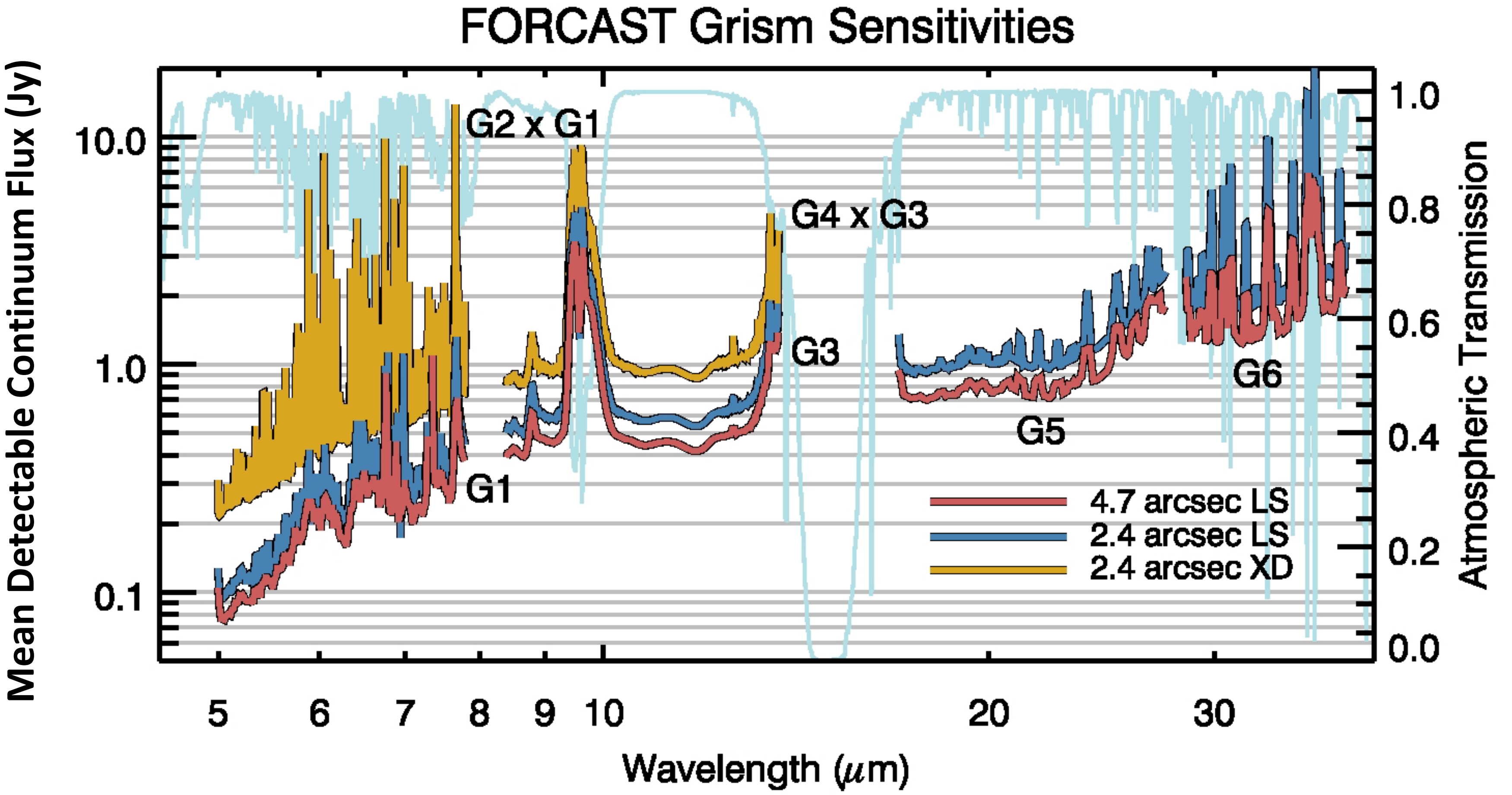
*Note that IR lines of [Na III] 7.32μm, [Na IV] 9.04 μm, 21.29 μm, [Na VI] 8.61 μm, 14.33 μm, and [Na VIII] 6.23 μm, 13.66 μm are predicted to occur but have never yet been detected

Nova Research with SOFIA FORCAST

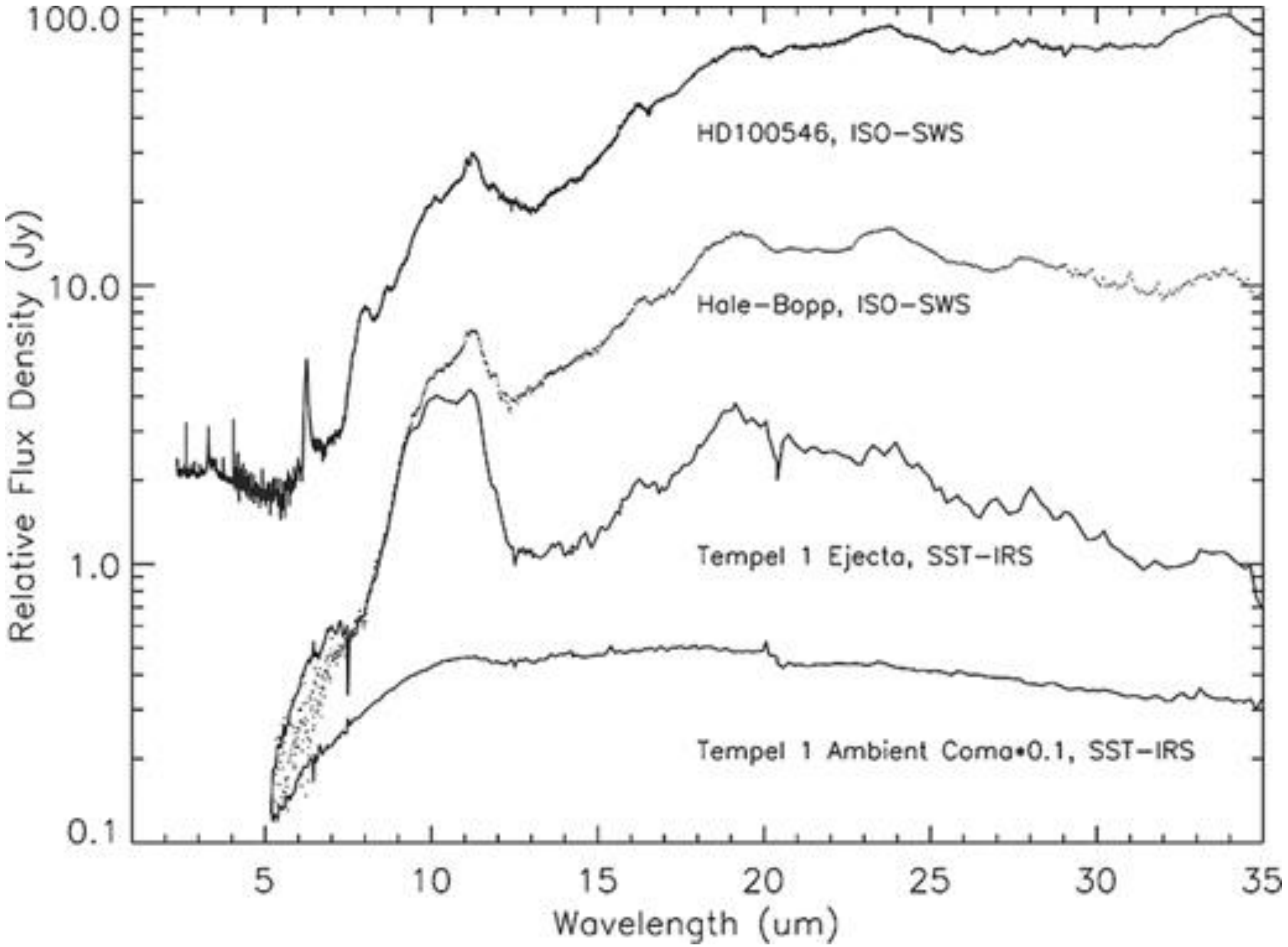
The NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA) Clipper Lindbergh

- 2.5-m clear aperture airborne telescope flying at 45,000 feet altitude
- 4.9 – 37.1 μm with spectral resolutions from $R = \lambda/\Delta\lambda = 110$ to 160
- Covers most wavelengths and spectral resolutions needed to study nova dust mineralogy and abundances from IR forbidden emission lines

Spectroscopy with FORCAST Grisms



Dust Mineralogy with FORCAST Grisms



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, University of Minnesota

  D. P. K. Banerjee, Mt. Abu Observatory

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

  L. A. Helton, USRA/SOFIA

  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

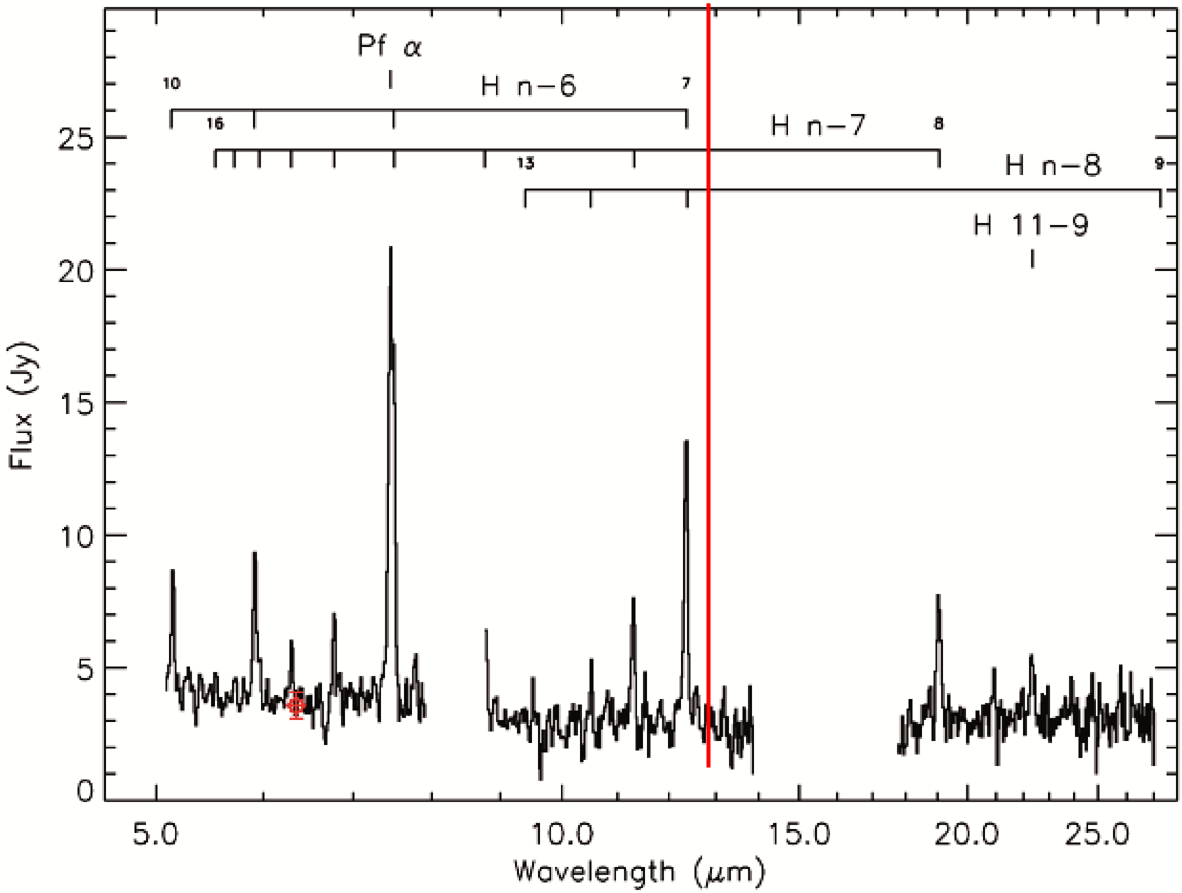
  R. M. Wagner, Large Binocular Telescope Observatory

"Physics of Evolved Stars 2015", Nice, France, 2015 June 09

Current and Future SOFIA Nova Programs

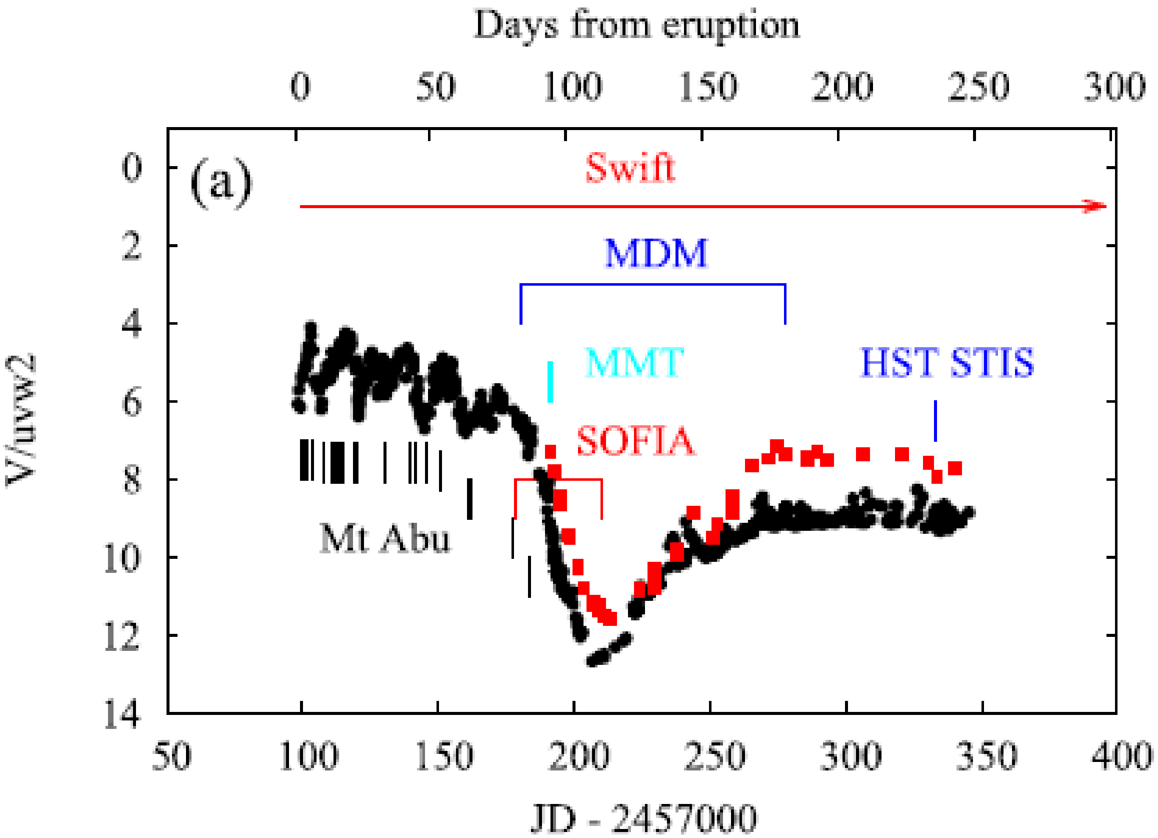
- **Past and Current SOFIA Nova Programs (38 hours)**
  - **R. D. Gehrz et al.: "Target of Opportunity observations of Classical Novae with SOFIA", 20 target-time hours over Cycles 1, 2, 3, 4, and 6**
  - **L. A. Helton et al.: "An Examination of Dust Formation and Destruction in the Classical Nova V1280 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 of Novae**
  - **The SOFIA Program Announces Observing Opportunities on an annual basis**
  - **The Cycle 7 call was issued on June 1, 2018.**

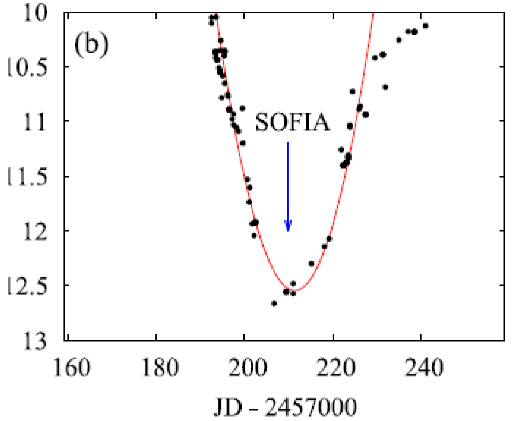
First Results: SOFIA FORCAST Grism Spectrum of V339 Del



- Pure Hydrogen emission spectrum – first to be observed beyond 13 μm
- Metallic forbidden lines are quenched at the high shell density of ~10^{11} cm^{-3}

SOFIA FORCAST ToO Observations of Grain Formation and Destruction in V5668 Sgr

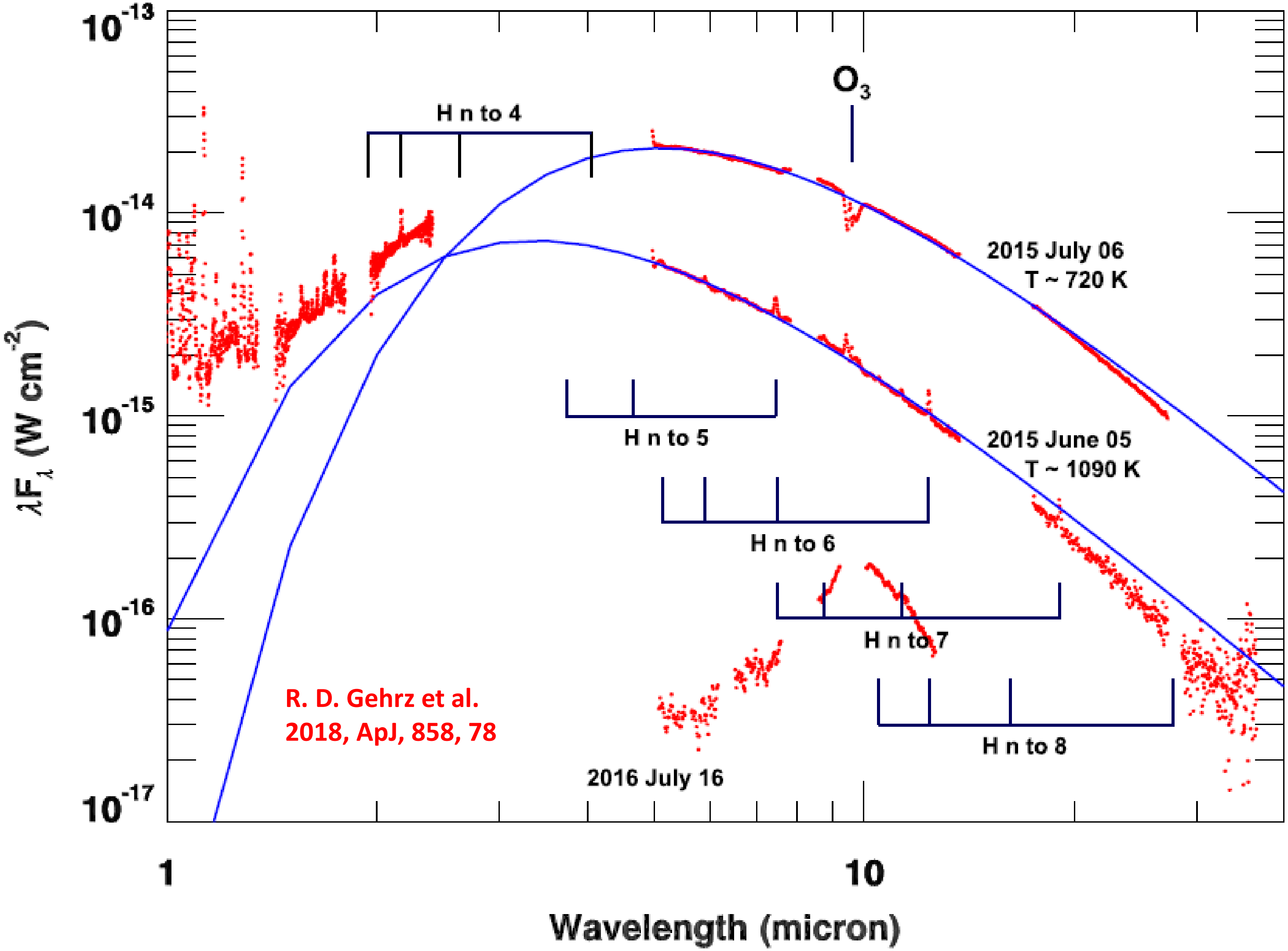




Maximum grain growth

R. D. Gehrz et al. 2018, ApJ, 858, 78

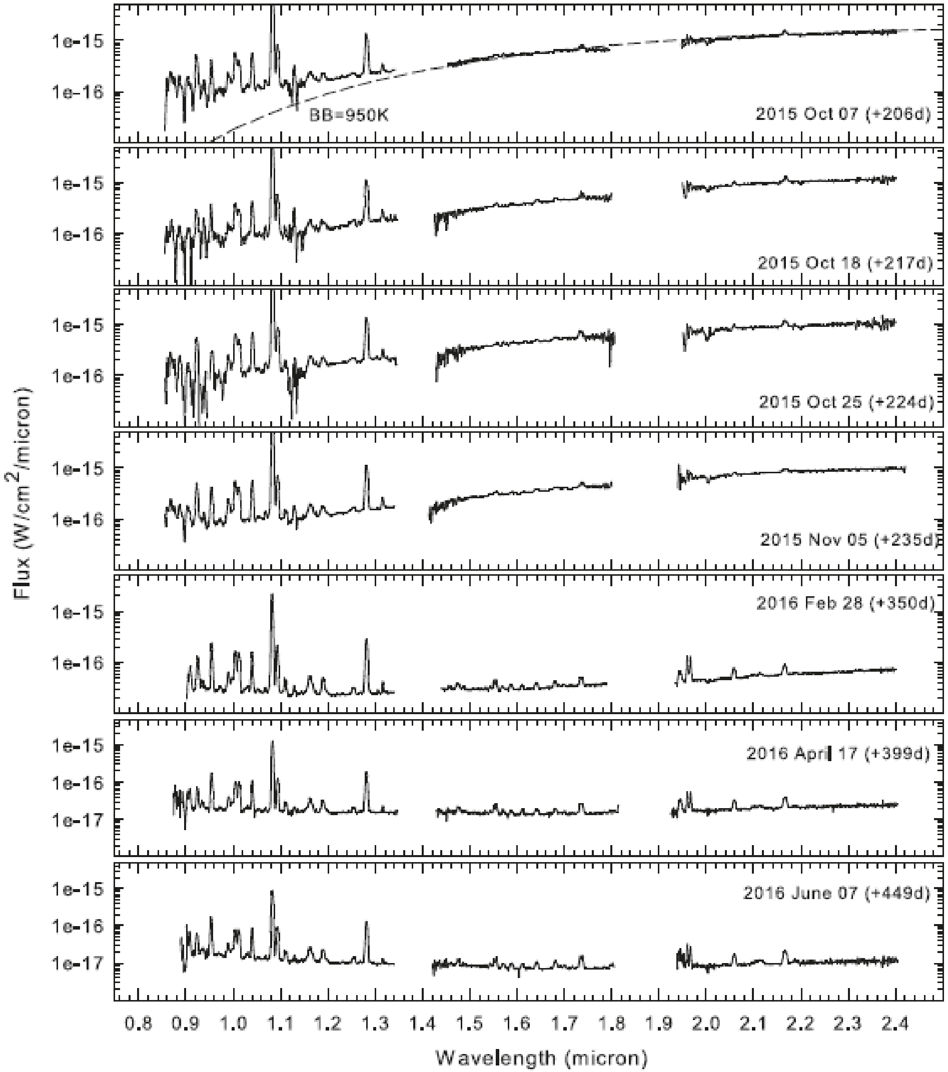
FORCAST Observations of Dust in V5668 Sgr



R. D. Gehrz et al.
2018, ApJ, 858, 78

IR Observations of Novae with SOFIA

Supplemental groundbased 0.9 - 2.4 μm near-IR specroscopy and photometry from Mt. Abu Observatory, India

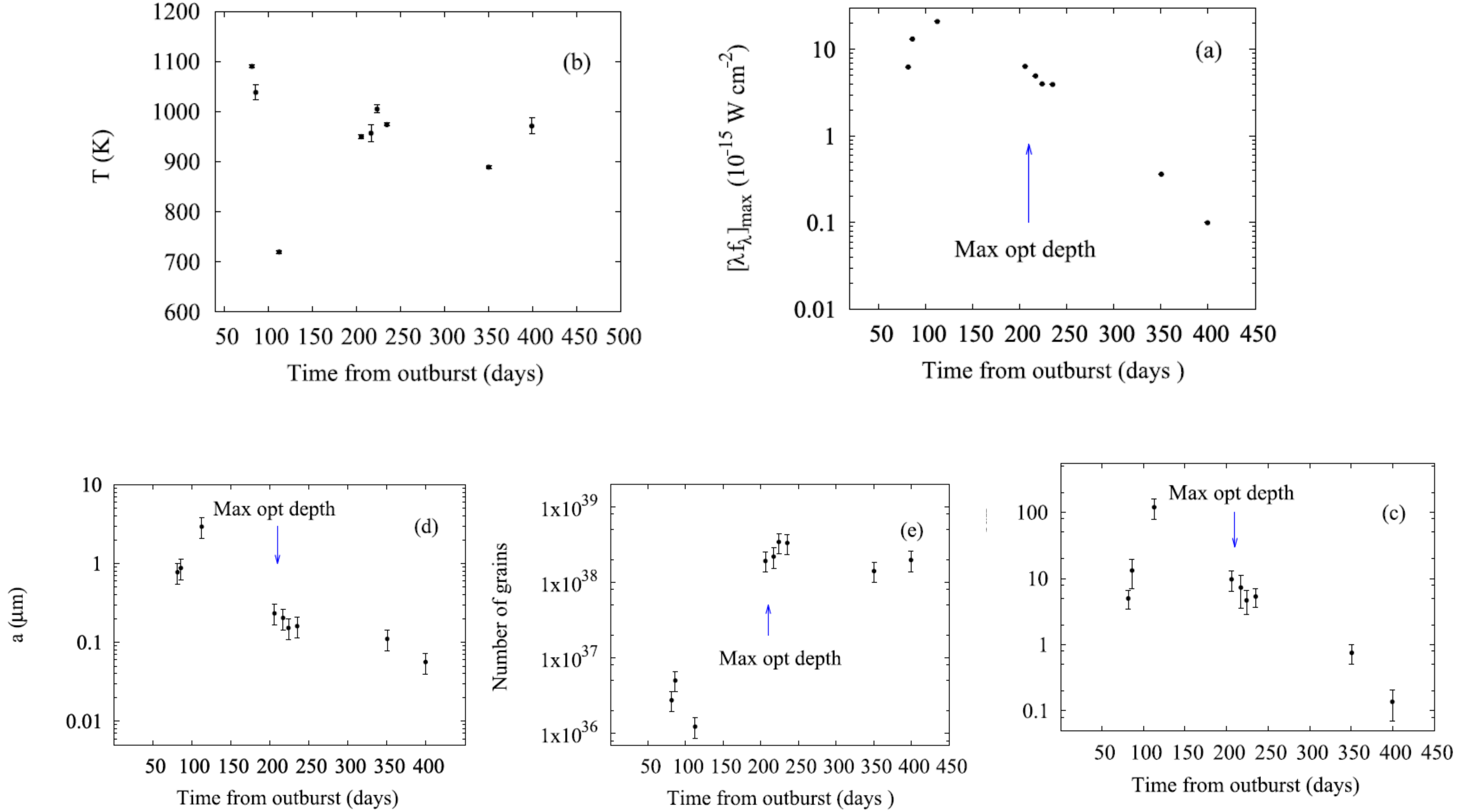


R. D. Gehrz et al. 2018, ApJ, 858, 78

Tracking Grain Size, Grain Number, and Dust Mass

- **Grain size:** $$a = \frac{L_o}{16\pi (V_o t)^2 A \sigma T^{(\beta+4)}}$$
- **Dust Mass:** $$M_{\mathrm{dust}} = 4.74 \times 10^{21} \frac{\rho_{\mathrm{d}} D^2 (\lambda F_\lambda)_{\max}}{A T^{(\beta+4)}} M_\odot ,$$
- **Grain Number:** $$N_{\mathrm{d}} = \frac{3 M_{\mathrm{d}}}{4 \pi a^3 \rho}$$
- ***A*** **and** β **are determined by grain mineralogy**

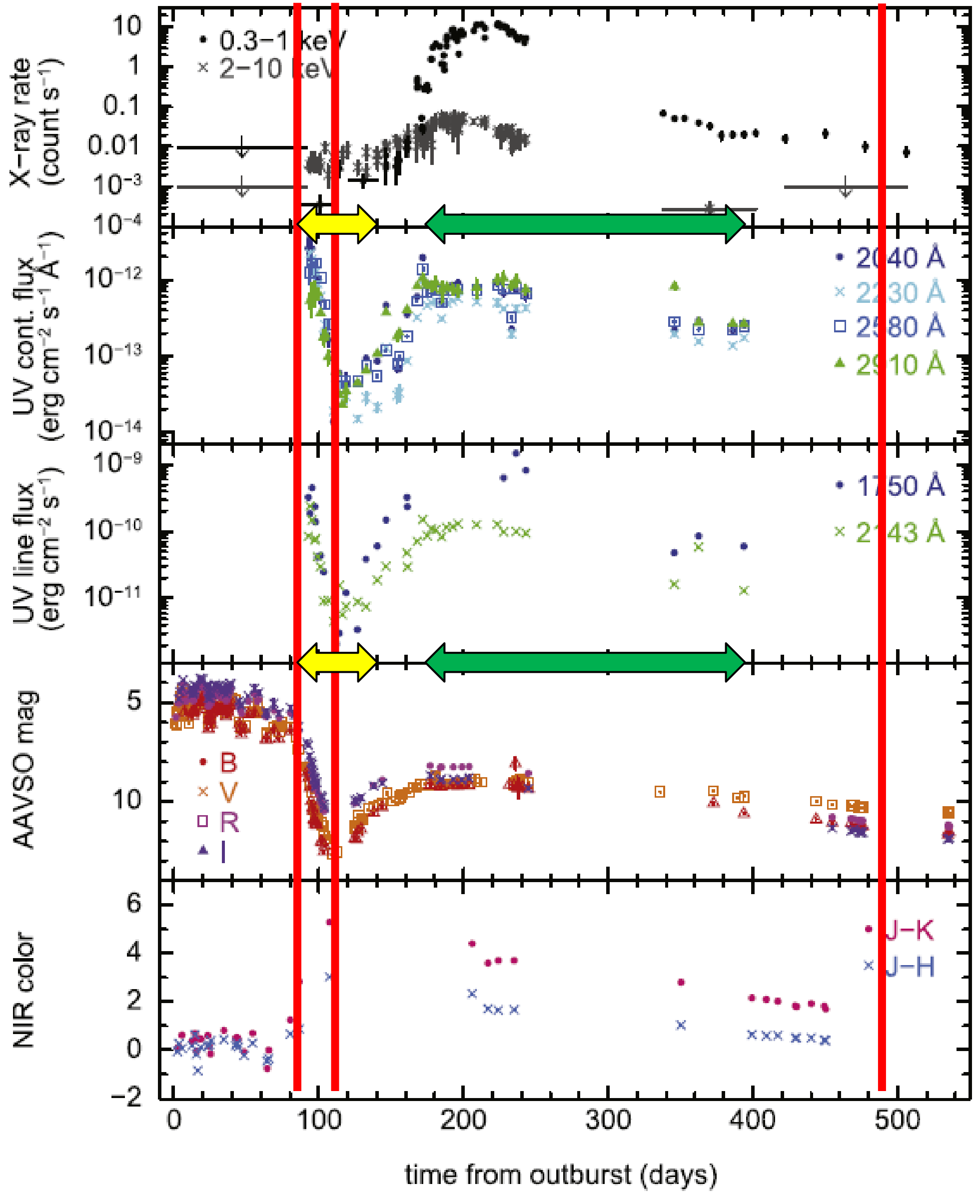
Tracking Grain Size, Grain Number, and Dust Mass



R. D. Gehrz et al. 2018, ApJ, 858, 78

IR Observations of Novae with SOFIA

X-Ray, UV, and V Temporal Development



SOFIA Spectra 🟥

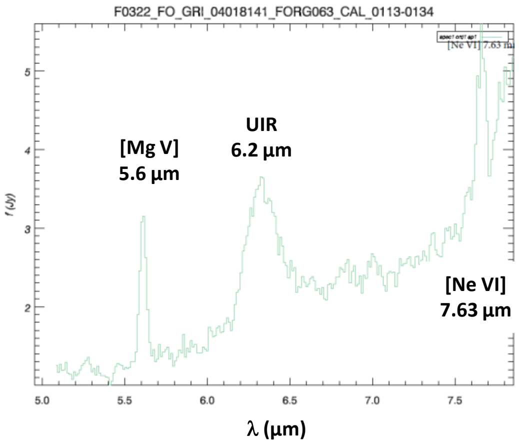
Grain Growth ⟺

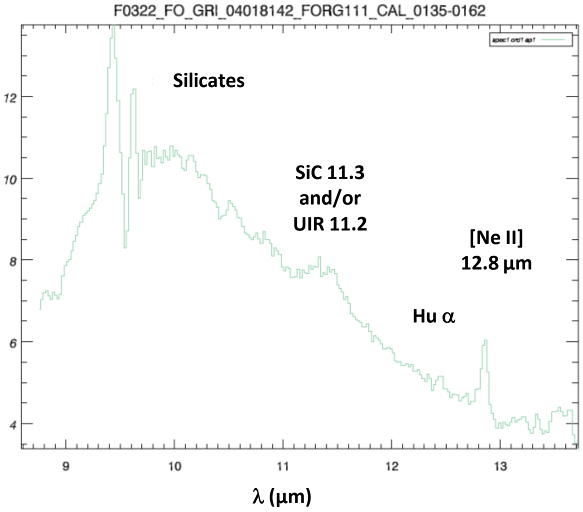
Grain Destruction ⟺

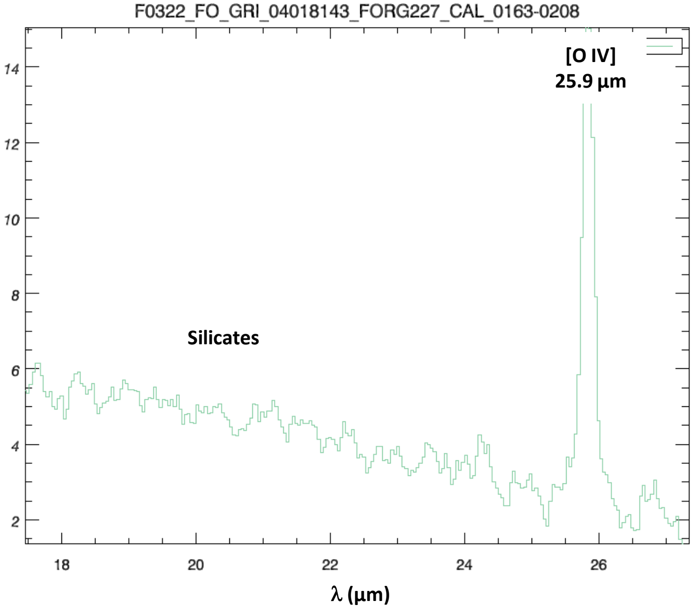
R. D. Gehrz et al. 2018, ApJ, 858, 78

IR SED on Day 488

L. A. Helton et al. 2018, in preparation







- **Dust emission dominated by silicates**
- **Hydrocarbons are present**
- **There are strong forbidden lines of Ne and O**

Summary

- **SOFIA FORCAST grisms cover the IR spectral range where metallic forbidden lines and dust emission features occur**

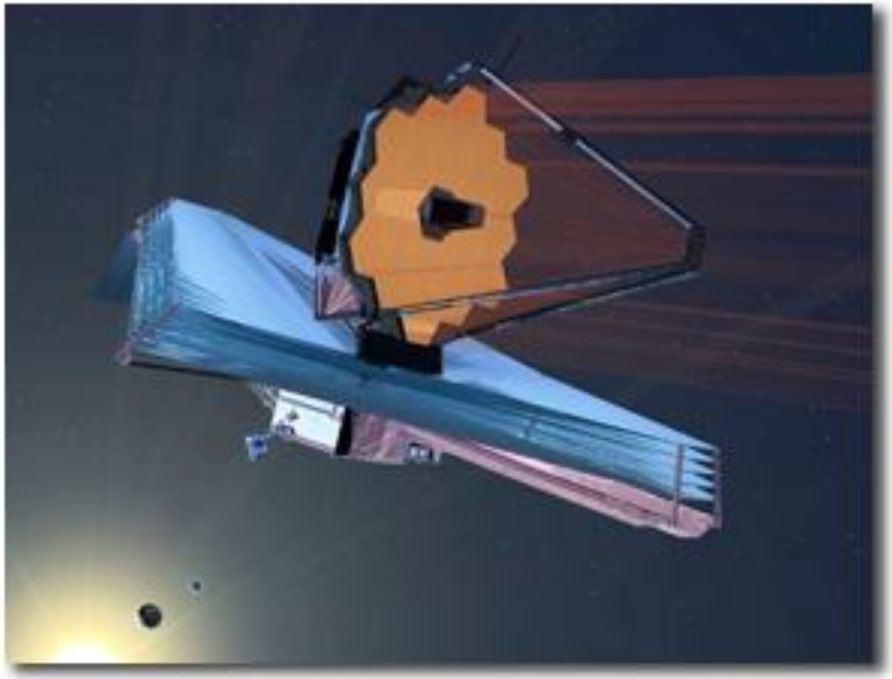
- **SOFIA can observe many lines and dust features that are not available from the ground**

- **The spectral resolution is appropriate for determining abundances and mineralogy**

- **SOFIA can fly anywhere and any time to respond to transient events**

Supplement: The future of Nova Observations with JWST

JWST: 2021 March 30 Launch



- ~ 6.5-m aperture 30K telescope orbiting at L2
- 0.6 – 28 μm with spectral resolutions from $R = \lambda/\Delta\lambda = 100$ to 3,000
- IR spectroscopic studies of extragalactic nova populations
- IR spectroscopic imaging of old Galactic nova shells

Selected Near Infrared Forbidden Lines Accessible with JWST

SPECIES	λ_o (μm)	SPECIES	λ_o (μm)
[Si VI]	1.96	[Al V]	2.88
[Si VII]	2.47	[Al VI]	3.66
[Si IX]	3.92	[Al IX]	3.02
[Ca VIII]	2.32	[Mg VIII]	3.02

Selected Infrared Forbidden Lines with $\lambda_o > 5\mu m$ Accessible with JWST

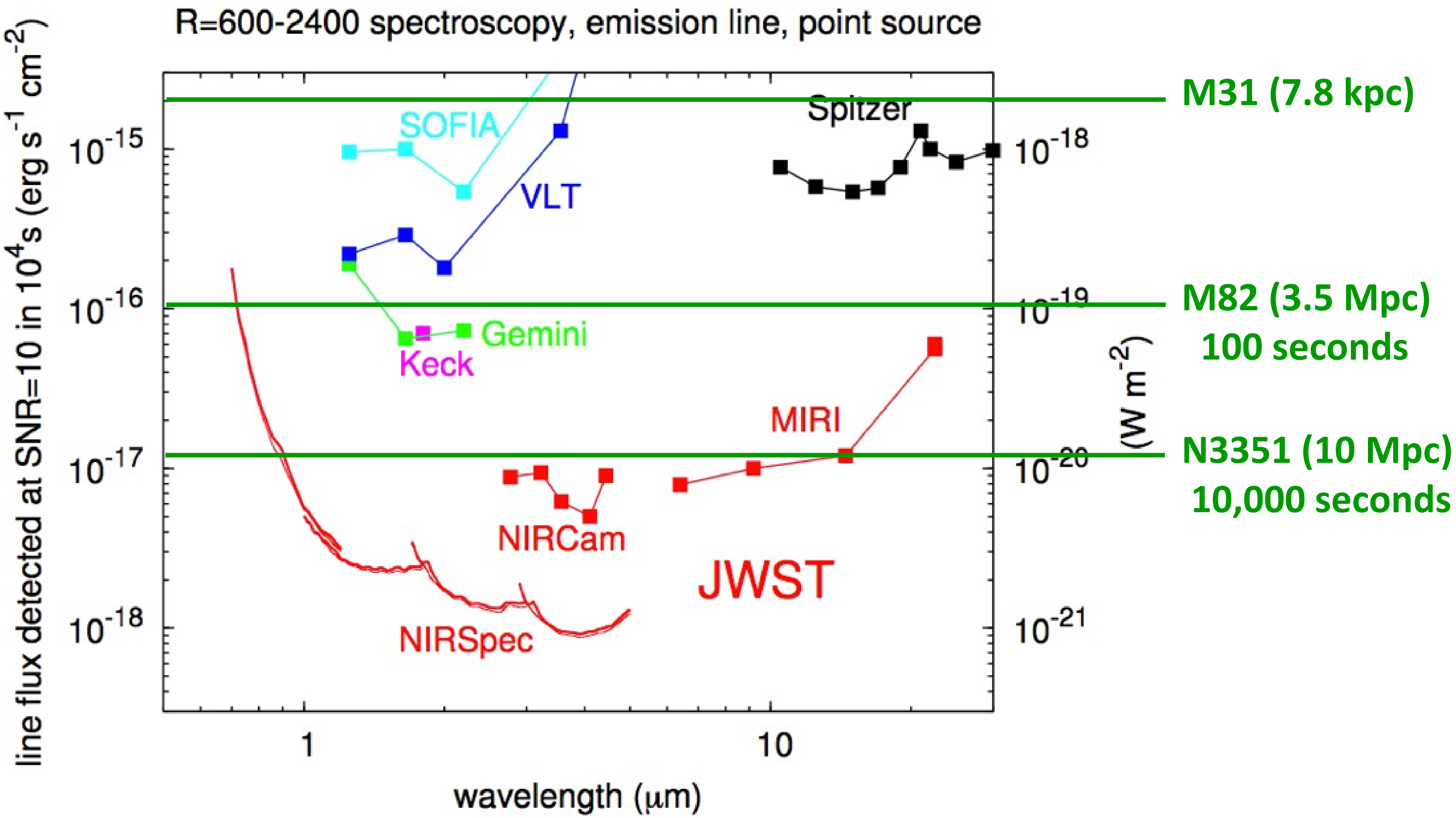
SPECIES	λ_o (μm)	SPECIES	λ_o (μm)	SPECIES	λ_o (μm)	SPECIES	λ_o (μm)
[O IV]	25.91	[Na VIII]*	6.23	[Al VIII]	5.85	[Si VII]	6.51
		[Na III]*	7.32	[Al X]	6.06	[Si VIII]	18.45
[Ne VI]	7.64	[Na VI]*	8.61	[Al VI]	9.12	[S IV]	10.51
[Ne II]	12.81	[Na IV]*	9.04			[S V]	27.10
[Ne VII]	22.0	[Na VIII]*	13.66	[Mg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

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

Template Galactic CO and ONeMg Novae

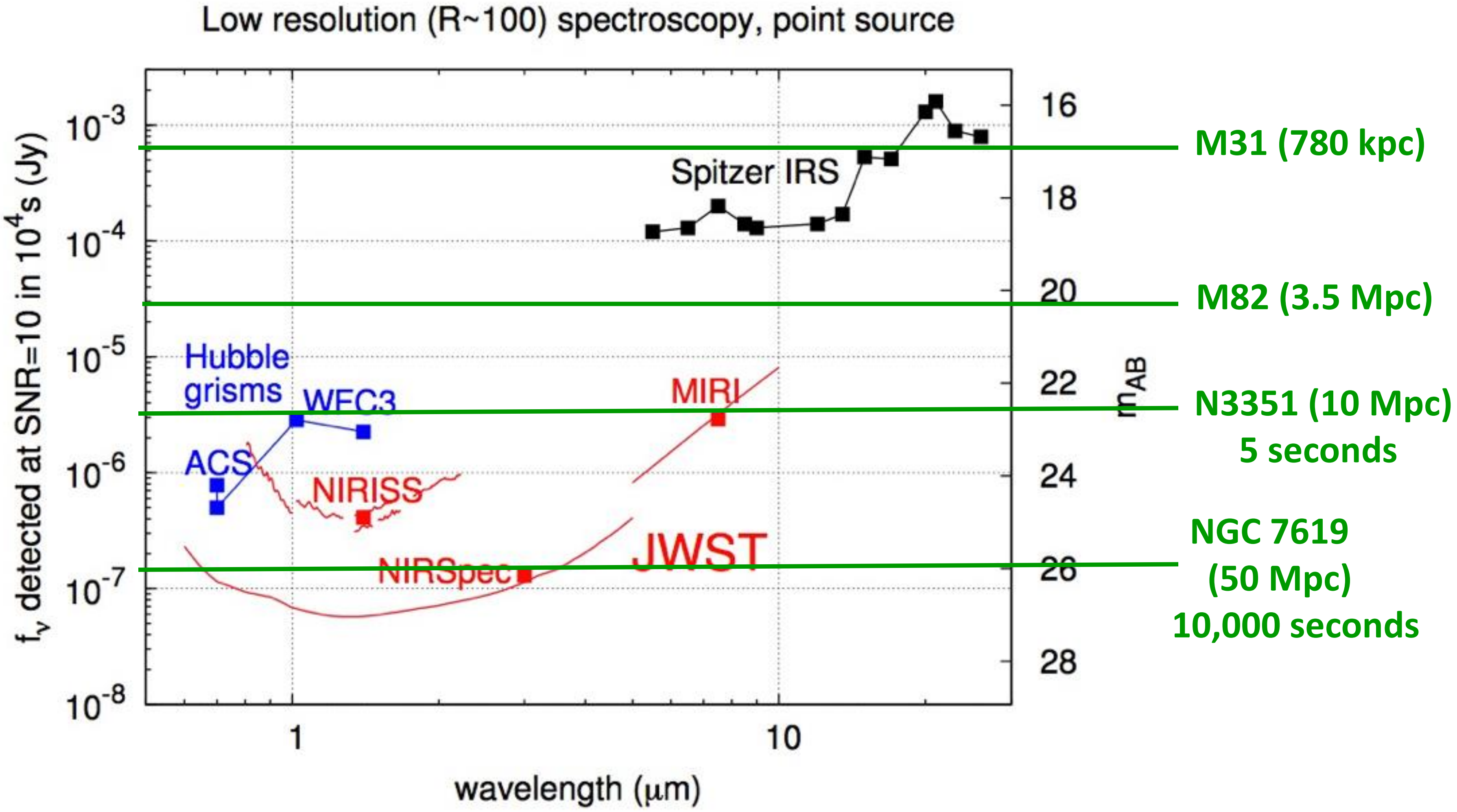
Nova	Type	D (kpc)	$M_{3.6\mu m}$ max	Time of 3.6μm maximum (days past outburst)	Absolute 3.6 μm Magnitude	Apparent 3.6 μm magnitude at 1 Mpc (flux in mJy)
V1668 Cyg	CO thin dust	4.6	+3.21	58	-10.06	+14.94 (0.29)
LW Ser	CO thick dust	5	+2.8	75	-10.69	+14.31 (0.53)
QU Vul	ONeMg	3	4.12	<140	-8.27	+16.73 (0.06)
V1974 Cyg	ONeMg	1.9	+2.33	10	-9.06	+15.94 (0.12)

JWST HI-RES Sensitivity to the ONeMg Nova QU Vul



Flux detected at S/N = 10

JWST LO-RES Sensitivity to the CO Nova NQ Vul



M31 (780 kpc)

M82 (3.5 Mpc)

N3351 (10 Mpc)
5 seconds

NGC 7619
(50 Mpc)
10,000 seconds

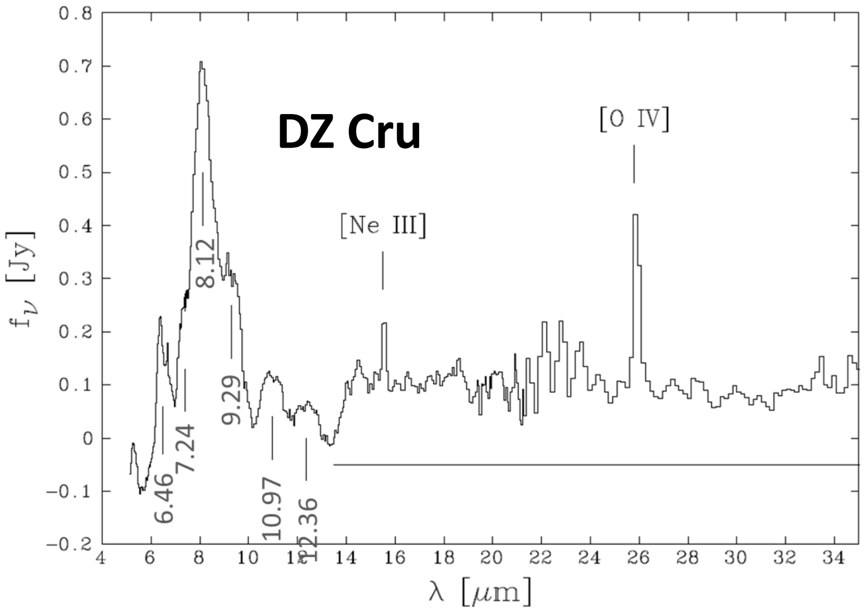
Flux detected at S/N = 10

Summary and Conclusions

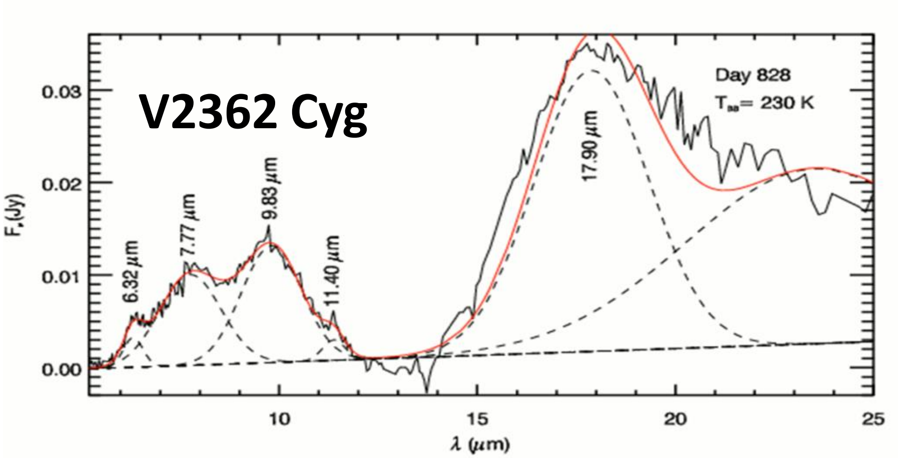
- IR data yield quantitative estimates for physical parameters characterizing the nova outburst
- Nova ejecta produce all known types of astrophysical grains: amorphous carbon, SiC, hydrocarbons, and silicates.
- Nova ejecta have large overabundances (factors of 10 to more than 100) of CNO, Ne, Mg, Al, S, Si
- Future prospects for IR observations of extragalactic classical novae and old Galactic nova shells JWST are promising

Backup

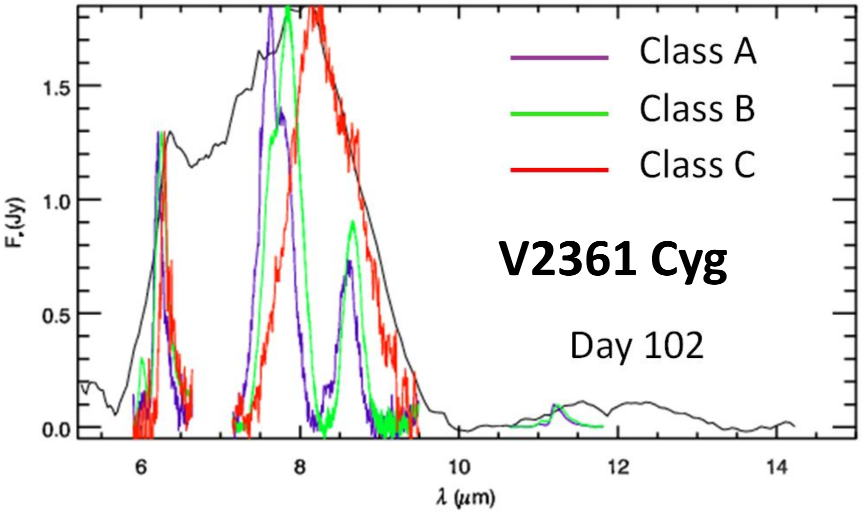
Spitzer Spectra of Hydrocarbon Grains in CNe



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



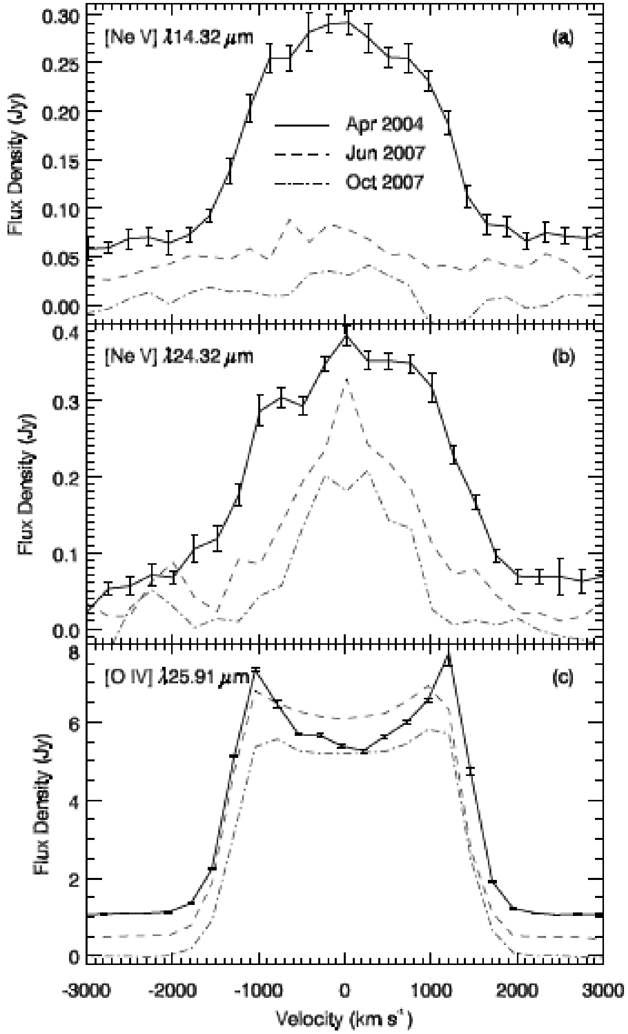
See L. A. Helton, et al. 2011, EAS Publications Series, 46, 407



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

- **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**

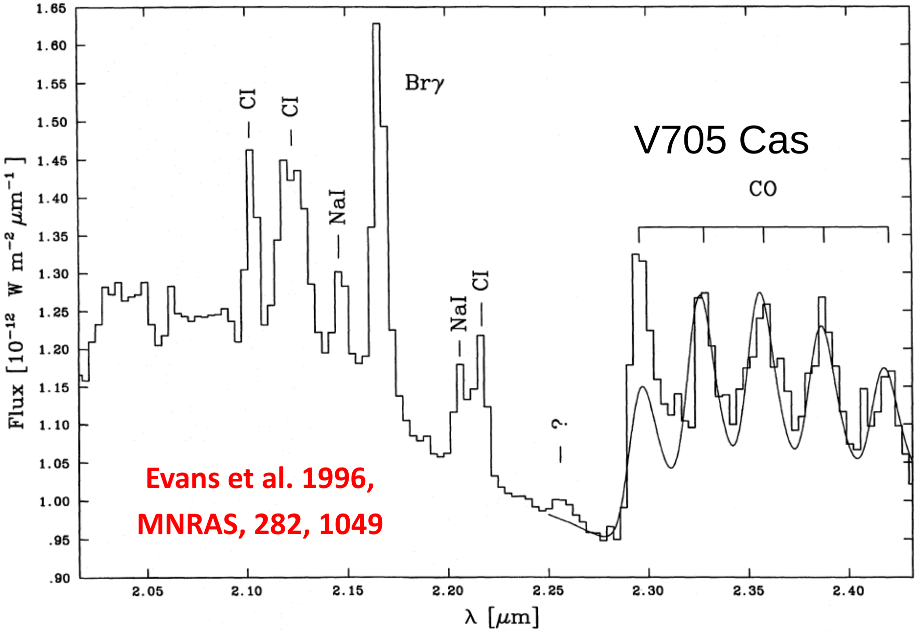
Velocity Resolved *Spitzer* Spectra:V1494 Aql



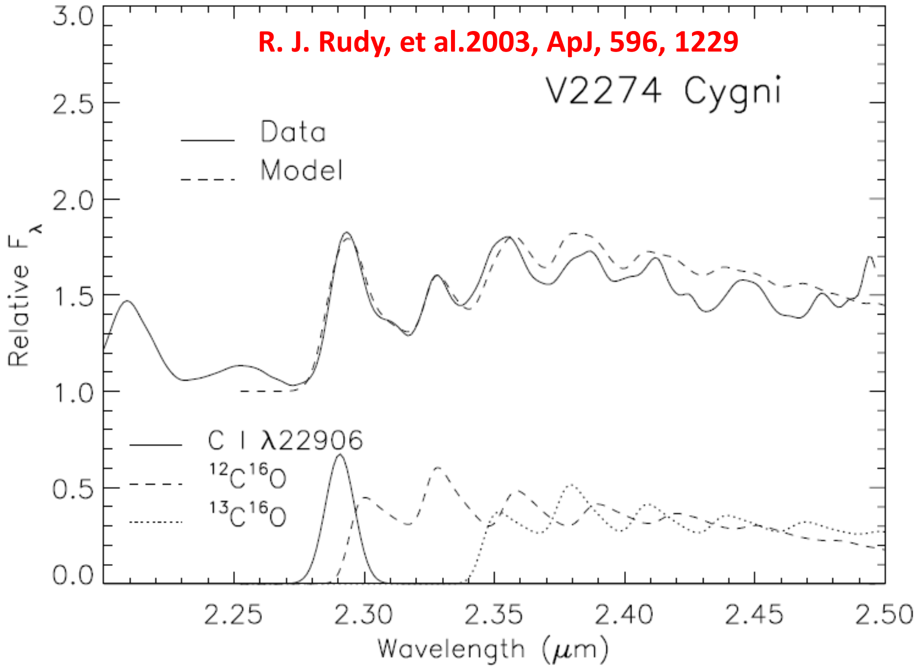
Line shapes reveal kinematic structure associated with different ionization potentials

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

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)