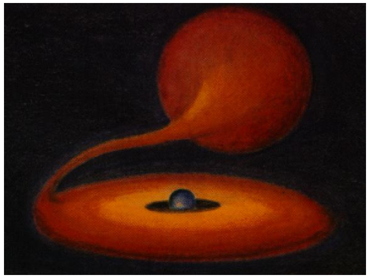
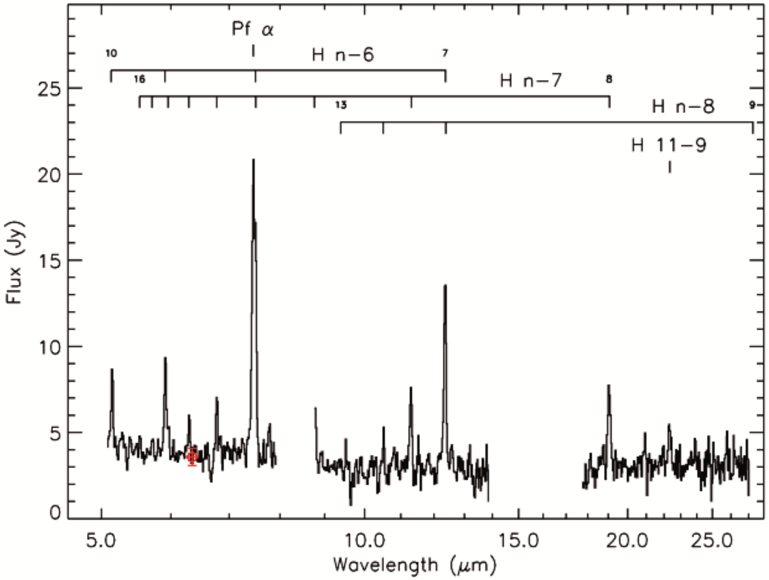
Infrared Observations of Novae in the SOFIA Era





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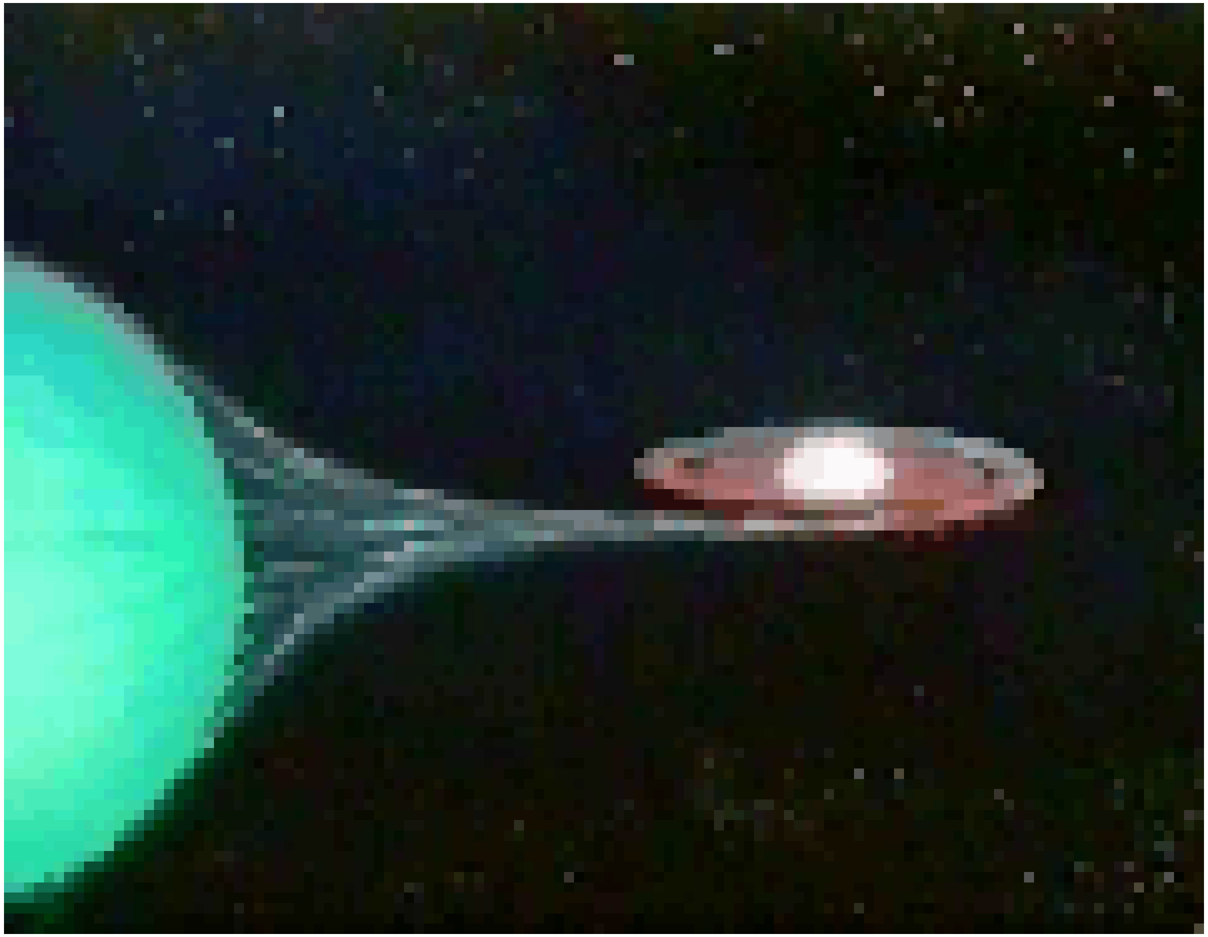
[c]USRA/SOFIA, NASA Ames Research Center, USA

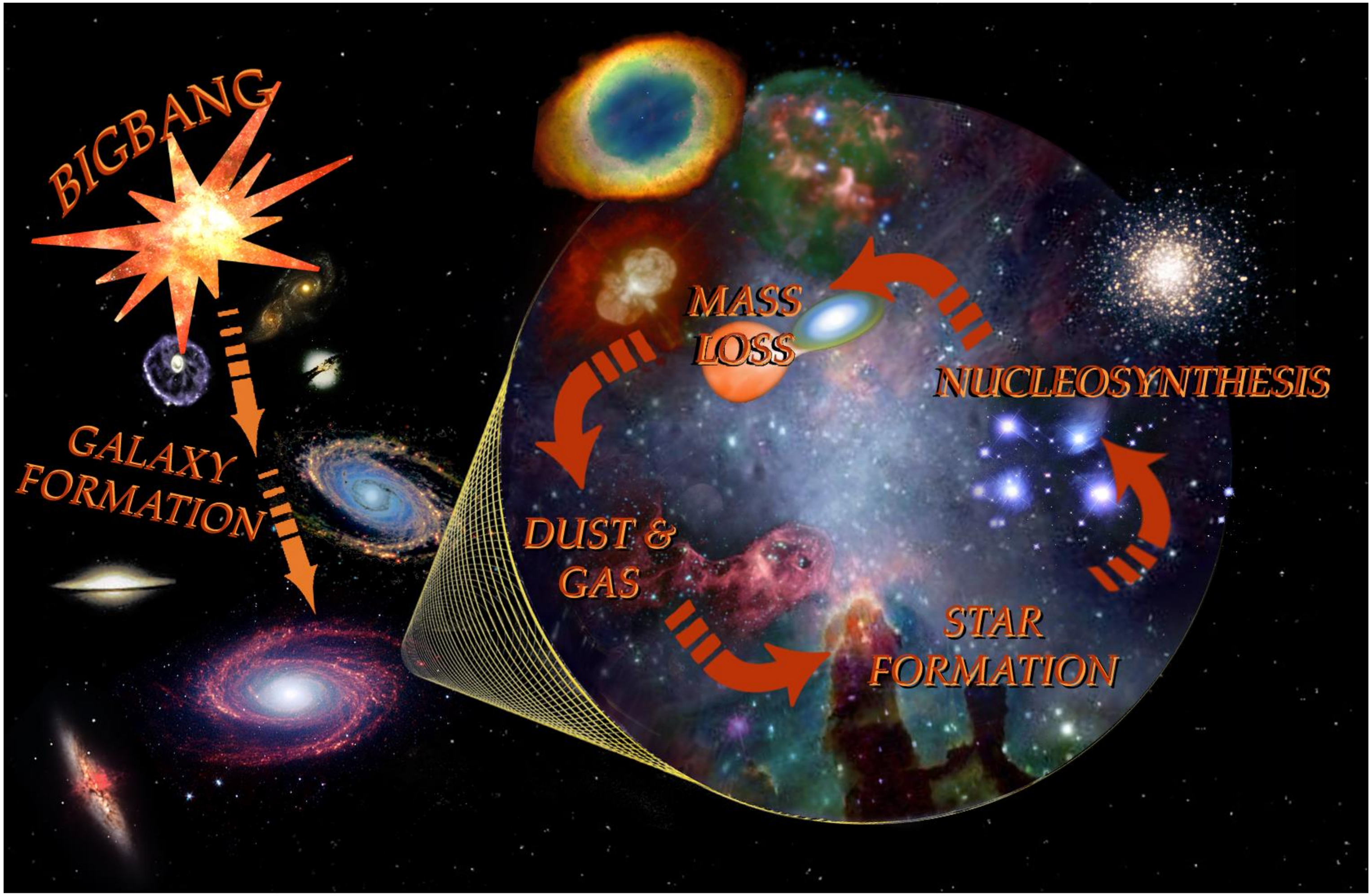
Outline

- *Novae and Galactic chemical evolution*
- *IR Observations of gas and grains in nova ejecta*
- *IR observations of novae with SOFIA*
- *Summary*

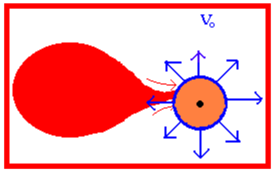
A Classical Nova Explosion: Accretion followed by a TNR



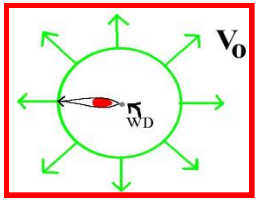
The Role of Classical Novae in Galactic Chemical Evolution



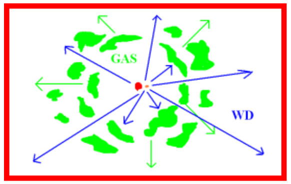
Infrared Development Phases



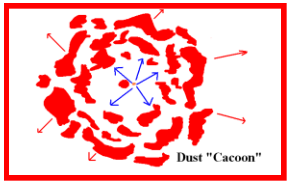
Fireball Expansion Phase



Free-Free Expansion Phase

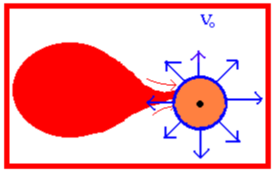


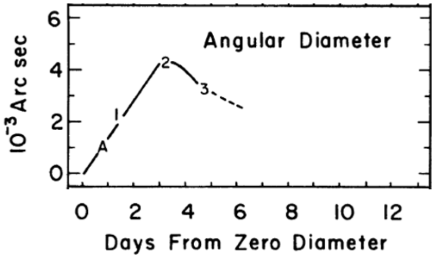
Coronal Phase in ONeMg Novae



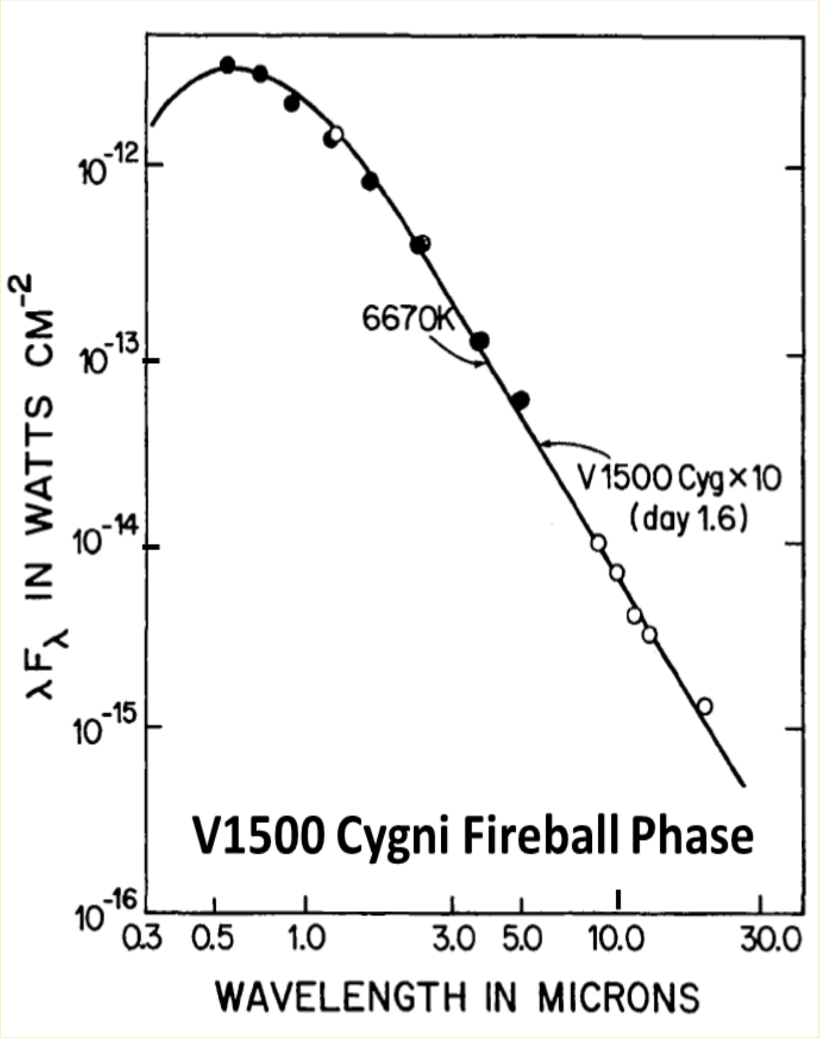
Dust Cocoon Phase in CO Novae

The Fireball Expansion Phase





Gallagher & Ney 1976



Gallagher & Ney 1976

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

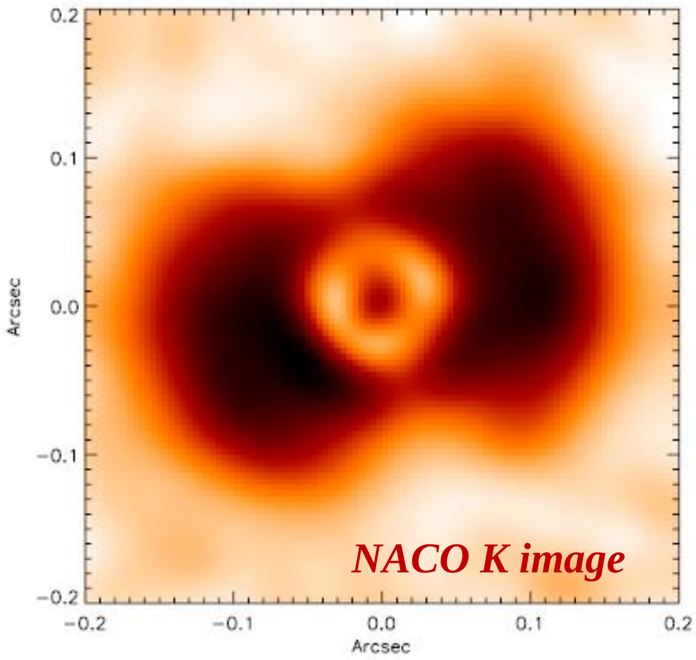
$$D = \frac{V_{out}t}{d\theta_{BB}/dt}$$

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

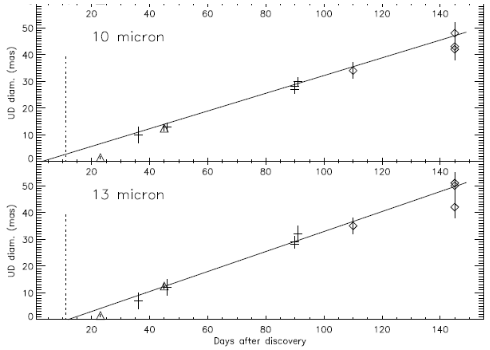
- ***The luminosity of the outburst fireball is*** $L_o \geq L_{Edd}$

Olivier Chesneau: Pioneering Early Nova Expansion Images

- ***Chesneau et al. (2012, A&A 545, 63) performed direct near-IR and mid-IR imaging with the ESO VLT VISIR, NACO, and SINFONI to determine the distance to Nova V1280 Sco by the angular expansion parallax method***
- ***Chesneau et al. (2008, A&A 487, 223) used the Very Large Telescope Interferometer (VLTI) to spatially resolve the dust formation phase of V1280 Sco and showed that the ejecta were bipolar***

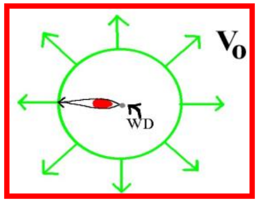


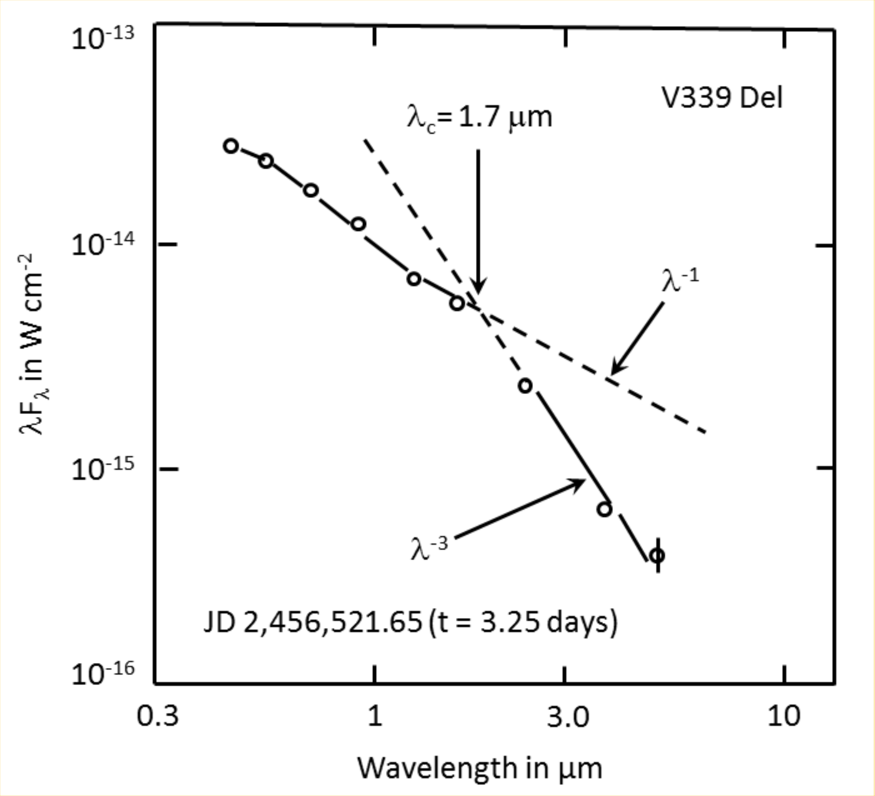
NACO K image



VLTI dust shell diameter with time

Free-Free Expansion Phase

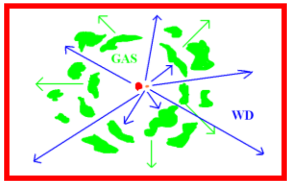


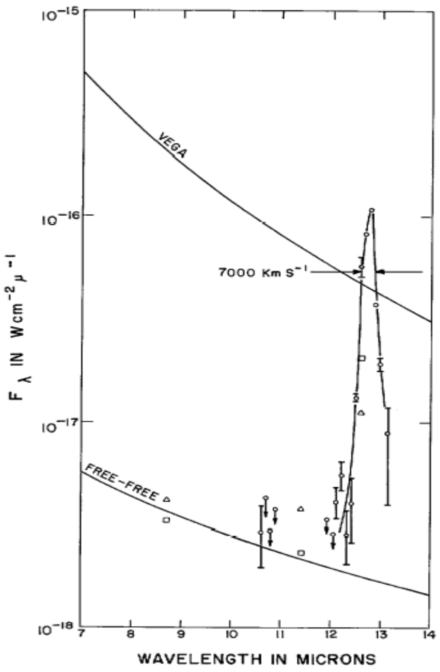


- *The cut-off wavelength, λ_c , where the optical depth is unity gives the shell density, n_H, and the mass of the ionized ejecta*
- $M_{gas} = \frac{4\pi}{3} n_H m_H (V_o t)^3$

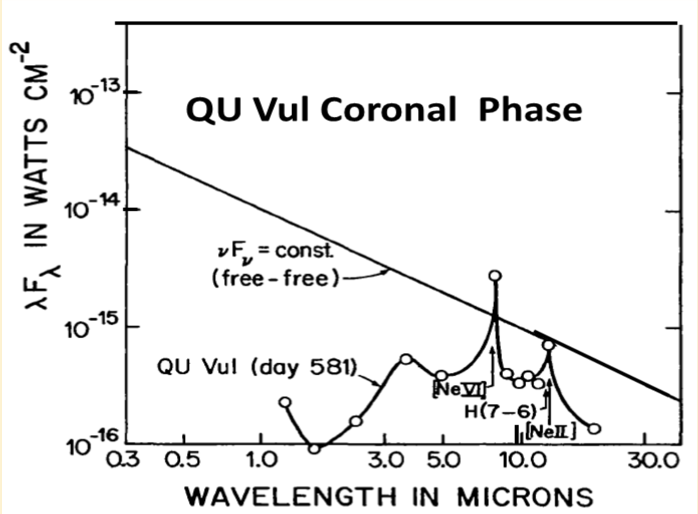
R. D. Gehrz, et al. 2015, ApJ, submitted

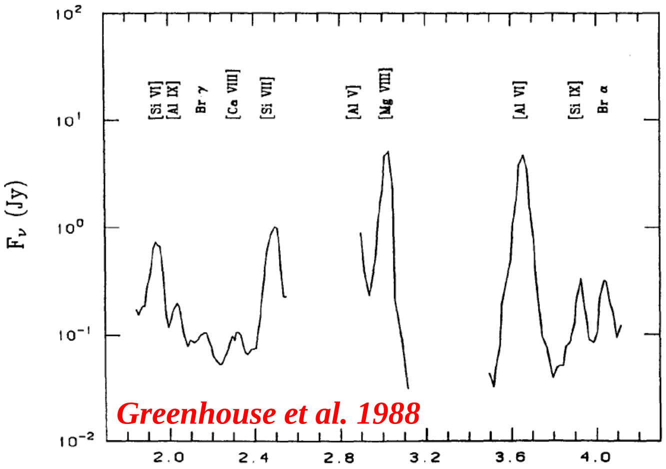
"Coronal" Emission Phase





Gehrz et al. 1985

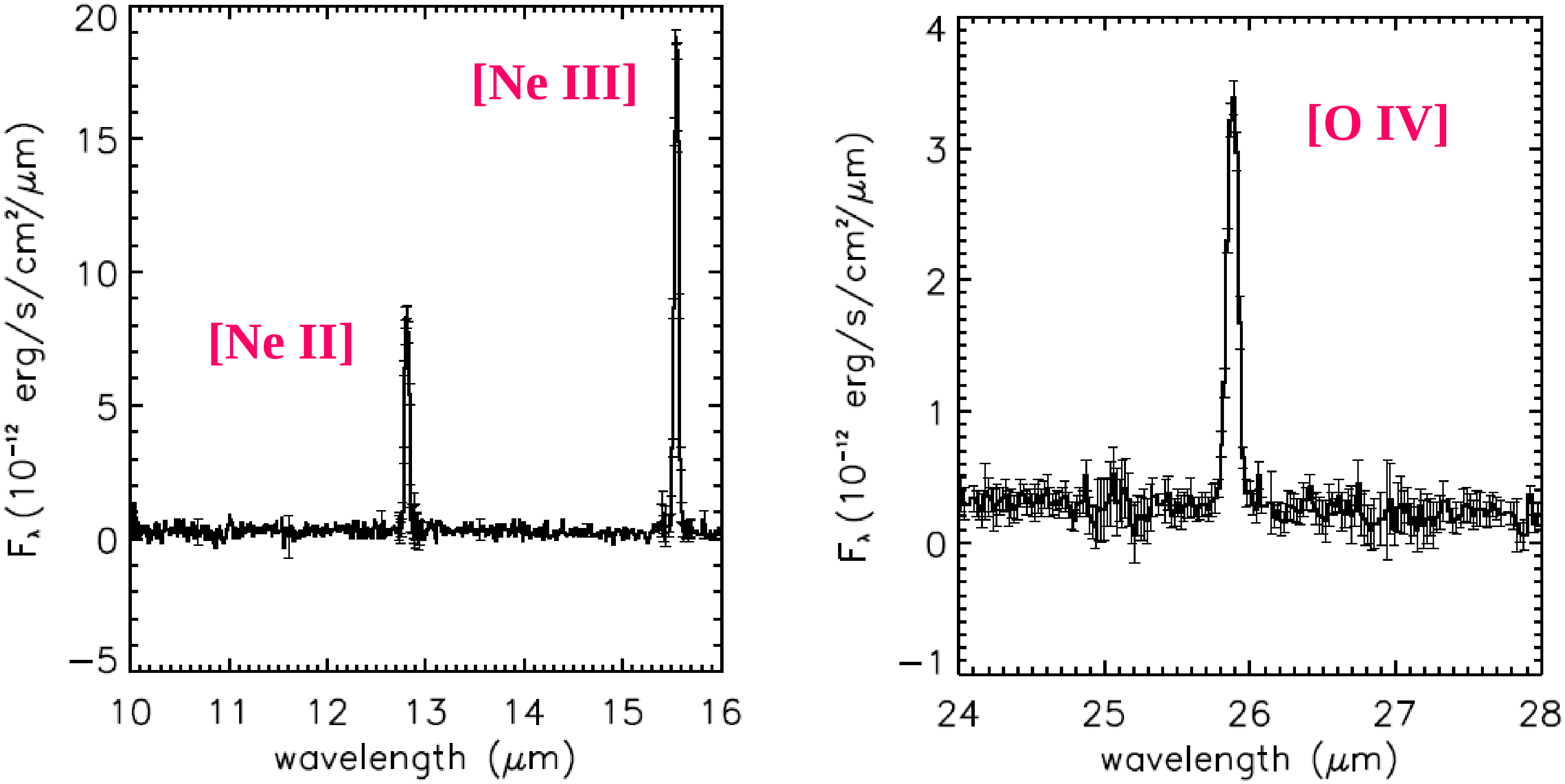




Greenhouse et al. 1988

- ***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

Determining Abundances from Forbidden Lines

- ***The high temperature central engine photo-ionizes the metals to forbidden upper levels that are then de-excited by electron collisions***

- ***The lines are optically thin so that the line luminosity is given by:***

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

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

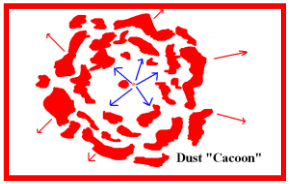
$$L_{free-free} = n_H^2 v_e (\sigma\Delta E)_{free-free} V_{shell}$$

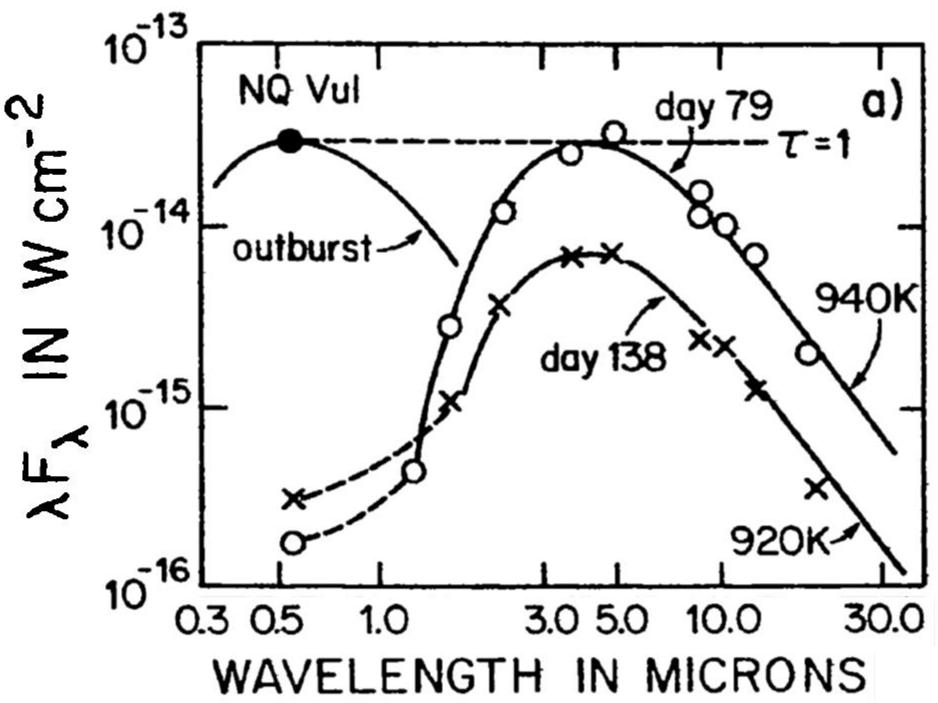
- ***So that the abundance for a single line is given by:***

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

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

Dust Formation Phase



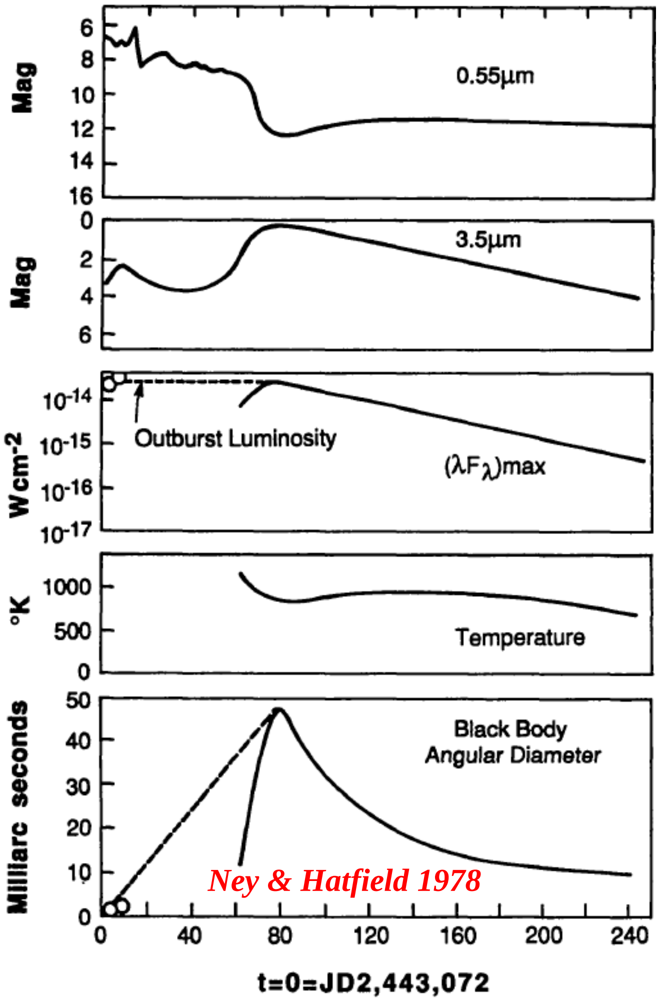


R. D. Gehrz (1988)

- *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

$$L_o \approx L_{Eddington}$$

$$T_c \approx 1000\ K$$

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

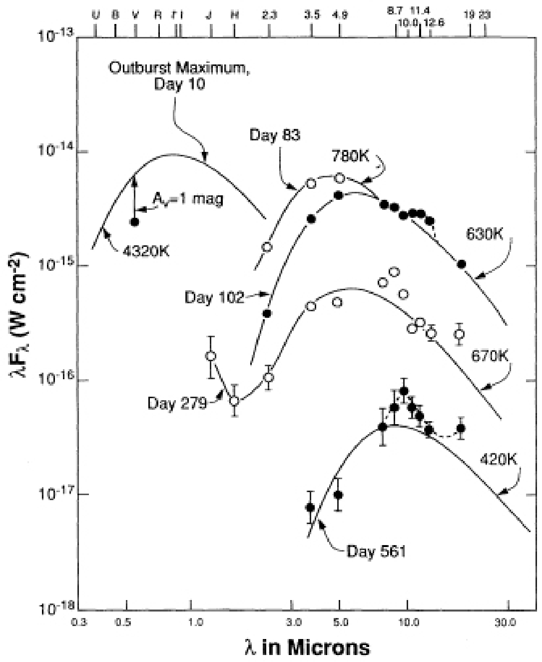
$$t_C \approx \frac{R_C}{V_O}$$

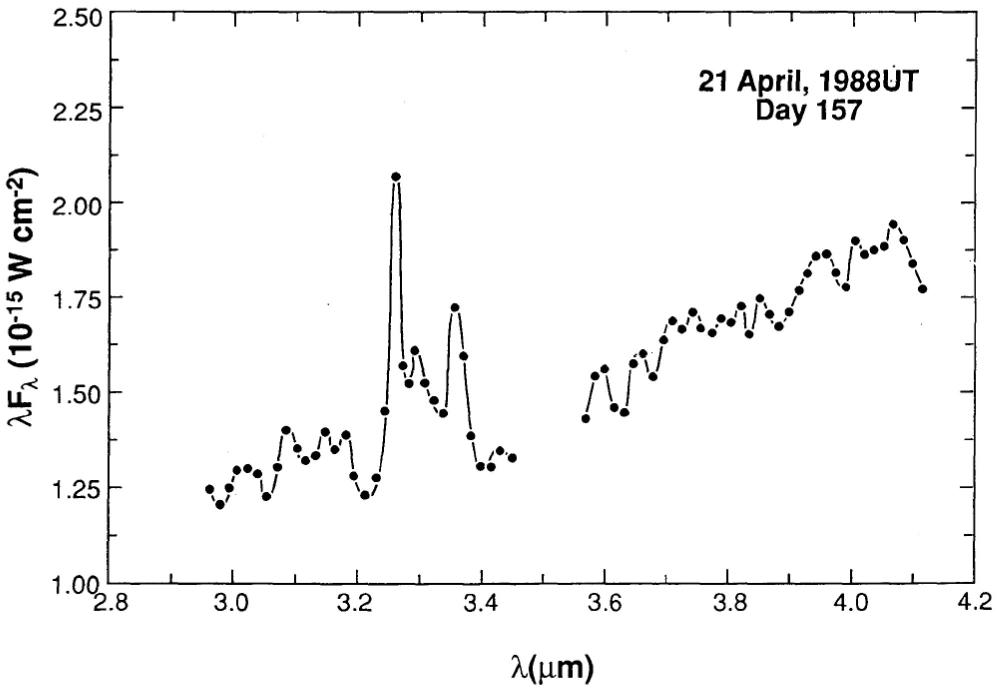
Nova Dust

- ***A small fraction (~20%) of classical novae form dust***
- ***Novae produce carbon, SiC, silicates, and hydrocarbons with emission features in the 5-40 μm spectral region***
- ***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

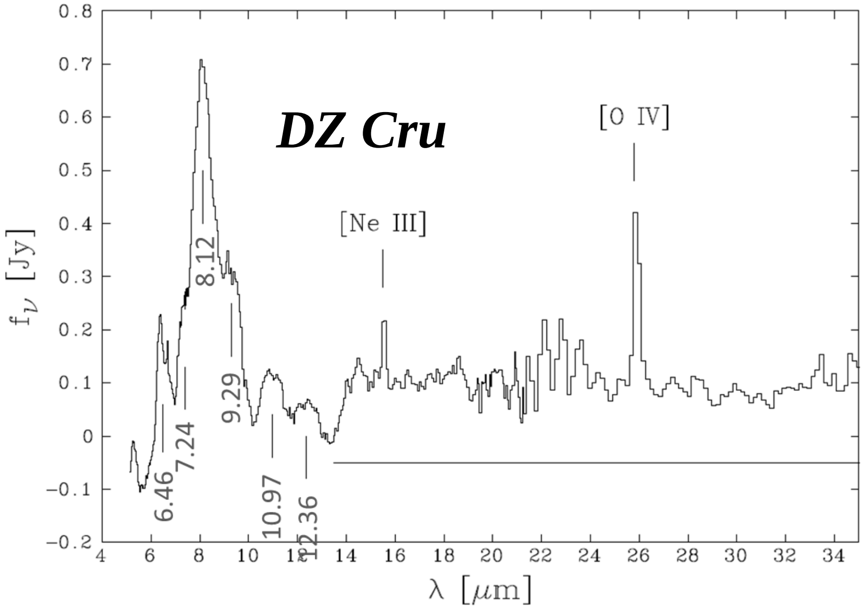
Gehrz et al. 1992 (Ap. J., 40, 671)



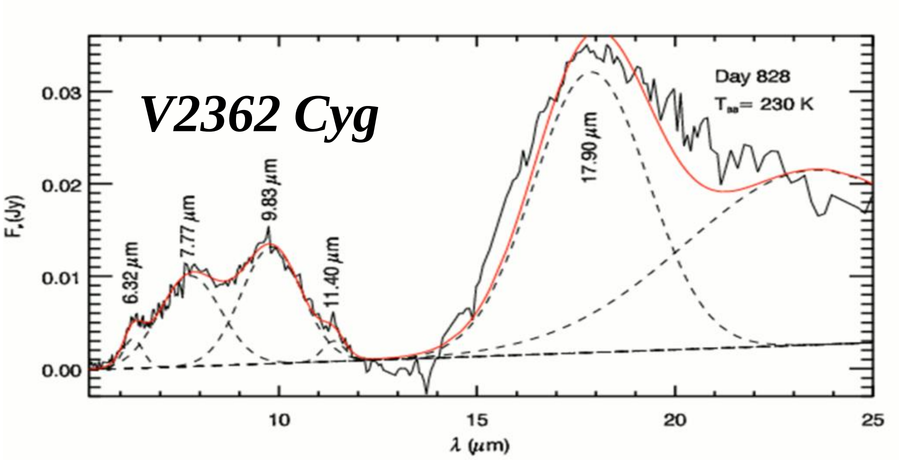


- *Carbon, Silicates, SiC, and PAH grains formed at different epochs in QV Vul suggesting abundance gradients in the ejecta.*
- *A. D. Scott (2000, MNRAS, 313, 775-782) has shown that this could be explained by an asymmetric ejection due to a TNR on a rotating WD*

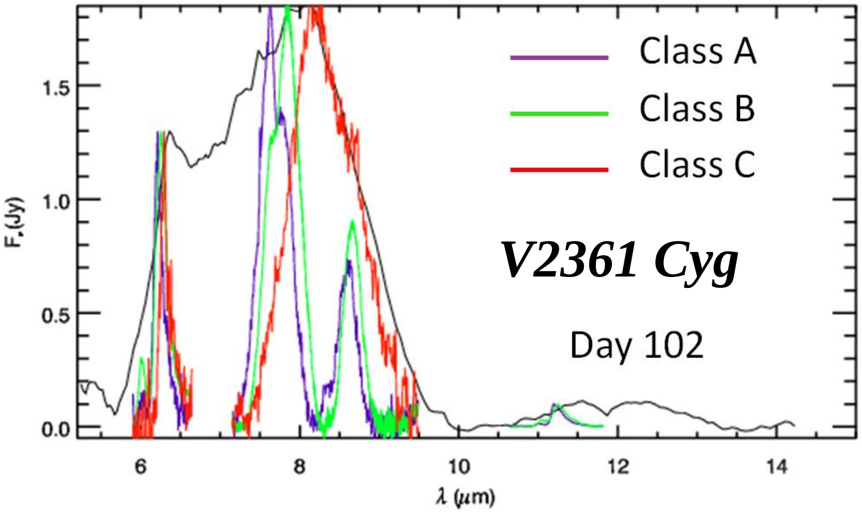
Spitzer Spectra of Hydrocarbon Grains in CNe



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



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*

Classical Novae and Abundance Anomalies

Evans and Gehrz (2012, BASI, 40, 213) and Gehrz, Truran, Williams, and Starrfield (1998, PASP, 110, 3) have concluded that novae may affect ISM abundances:

- *Novae process ≈0.3% of the ISM*
- $(dM/dt)_{novae} \approx 7 \times 10^{-3}\ M_{\odot}\ yr^{-1}$
- $(dM/dt)_{supernovae} \approx 6 \times 10^{-2}\ M_{\odot}\ yr^{-1}$

Novae may be important on a global Galactic scale if they produce isotopic abundances that are ≥10 times SN abundances and ≥100 times Solar abundances; Ejected Masses calculated from IR lines give a lower limit (not all the lines from all ionization states can be observed)

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

Nova	*X*	*Y*	$(n_X/n_Y)_{nova}$ $(n_X/n_Y)_{\odot}$	*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)*

Nova Research in the Infrared with SOFIA

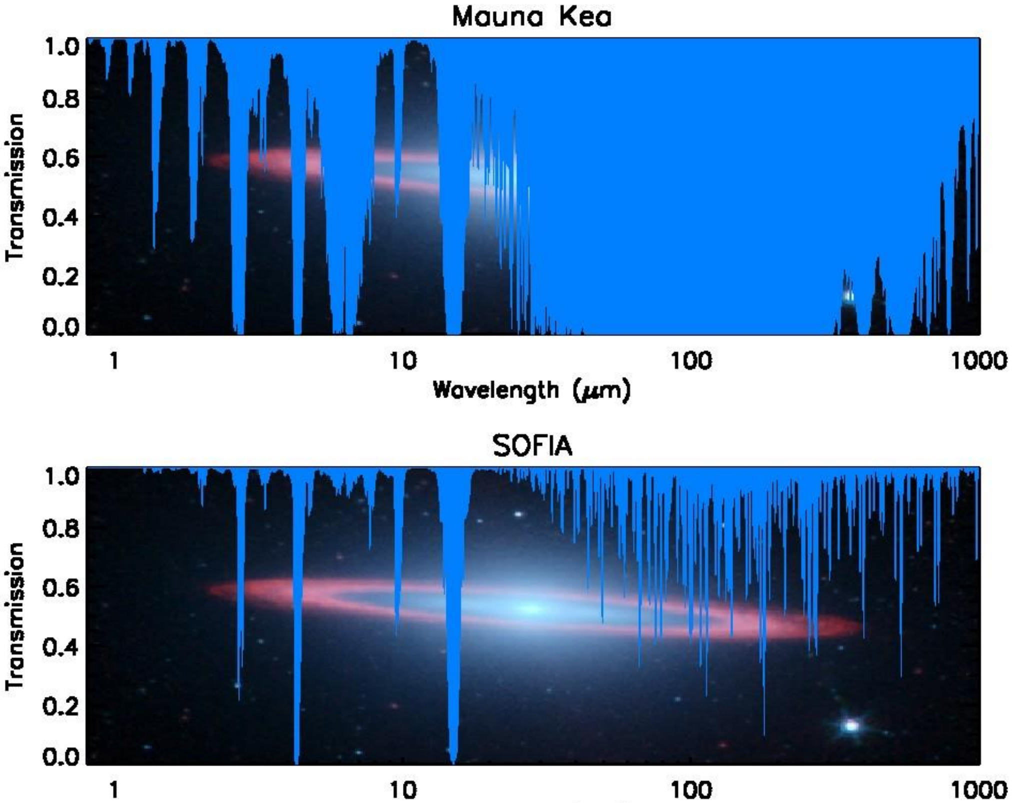
The NASA Stratospheric Observatory for Infrared Astronomy (SOFIA) Clipper Lindbergh

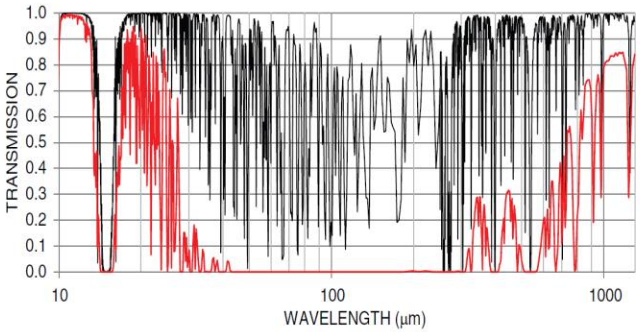
411260main_SOFIA_FirstDoorOpenFlight_480_DV.mov

- *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

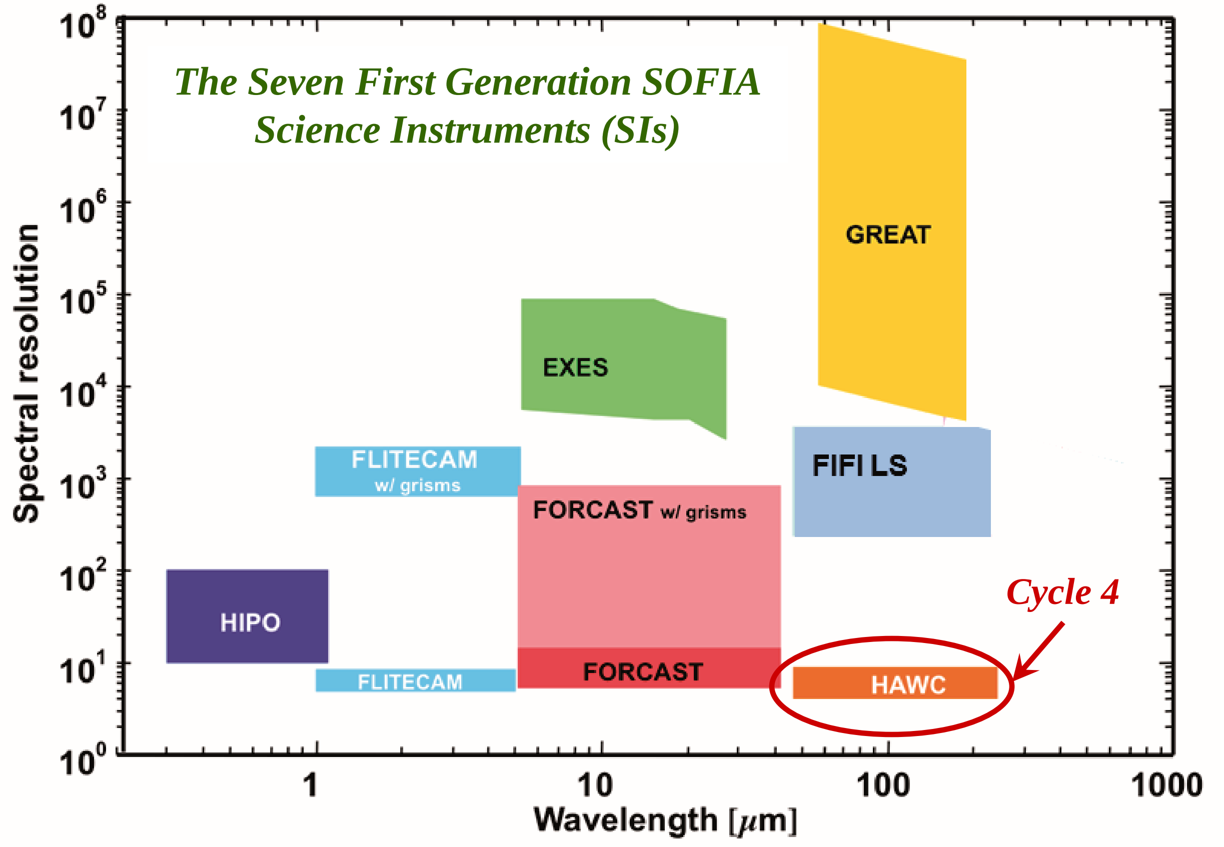
Cerro Chajnantor, 700μm Precipitable Water Vapor

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***
- ***4 SIs at Initial Operations; 7 SIs at Full Operations.***
- ***SOFIA will take advantage of improvements in instrument technology.***
- ***Will support both Facility Instruments and PI Class Instruments***


The Seven First Generation SOFIA Science Instruments (SIs)

Cycle 4

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

R. D. Gehrz

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

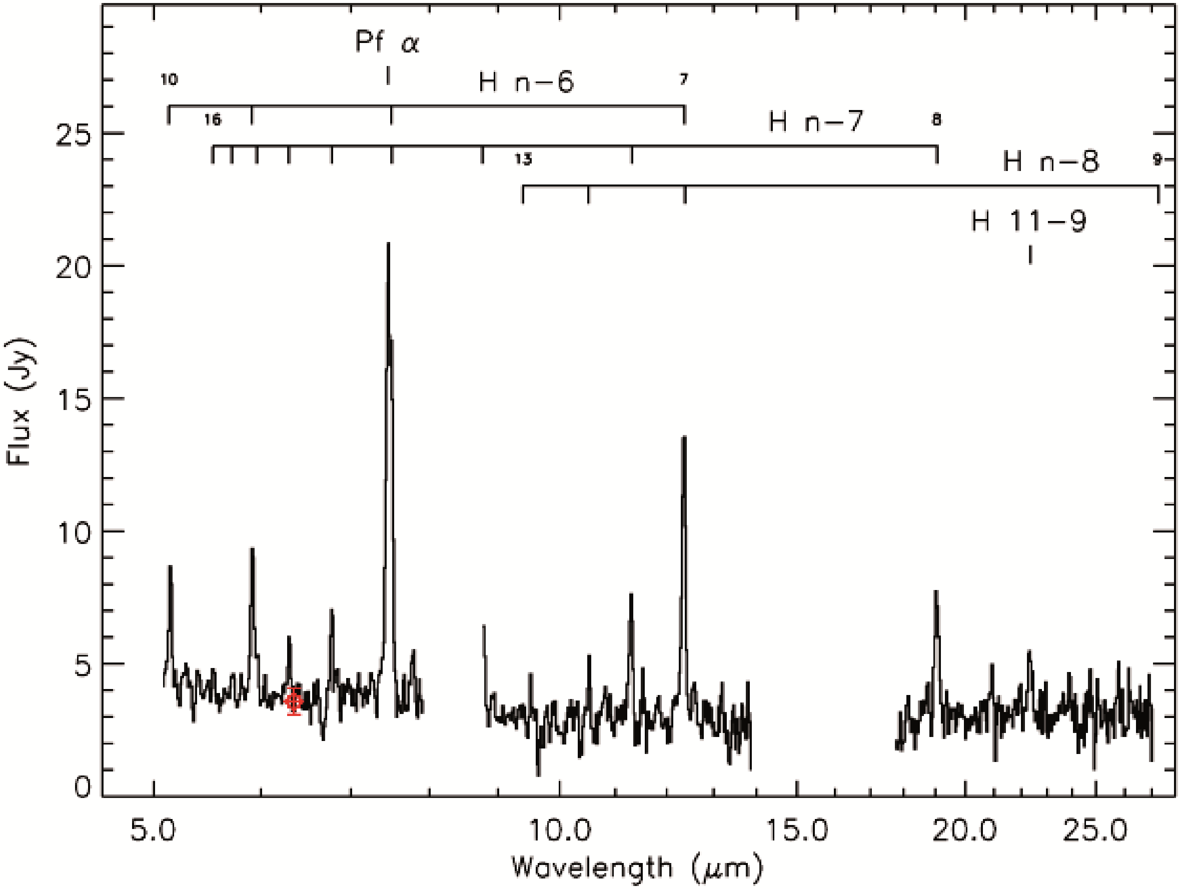
SPECIES	λ_O (μM)	SPECIES	λ_O (μM)	SPECIES	λ_O (μM)	SPECIES	λ_O (μM)
[O IV]	25.91	[Na VIII]*	6.23	[Al X]	6.06	[Mg V]	13.54
[O V]	32.61	[Na III]*	7.32	[Al VI]	9.12	[Si VII]	6.51
[Ne VI]	7.64	[Na VI]*	8.61	[Al VII]	37.6	[Si VIII]	18.45
[Ne II]	12.81	[Na IV]*	9.04	[Mg VII]	5.50	[Si II]	34.81
[Ne VII]	22.0	[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*

Current and Future SOFIA Nova Programs

- ***Past and Current SOFIA Nova Programs (26.8 hours)***
  - ***R. D. Gehrz et al.: "Target of Opportunity observations of Classical Novae with SOFIA", 16.8 target-time hours over Cycles 1, 2, and 3***
  - ***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***
- ***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 4 call was issued on May 1, 2015 and proposals will be harvested on July 10, 2015. The observing period will be from February 1, 2016 through January 31, 2017***

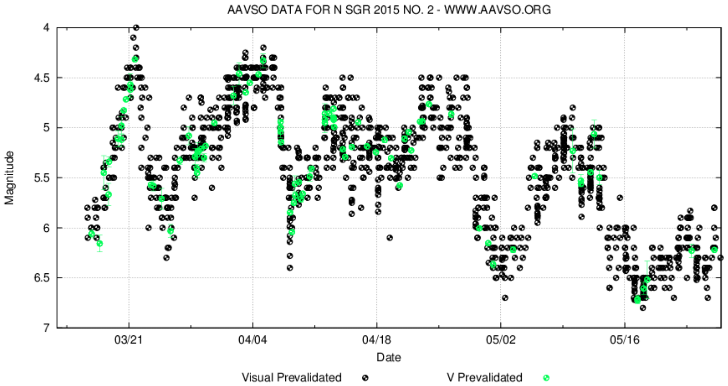
First Results: SOFIA FORCAST Grism Spectrum of V339 Del



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

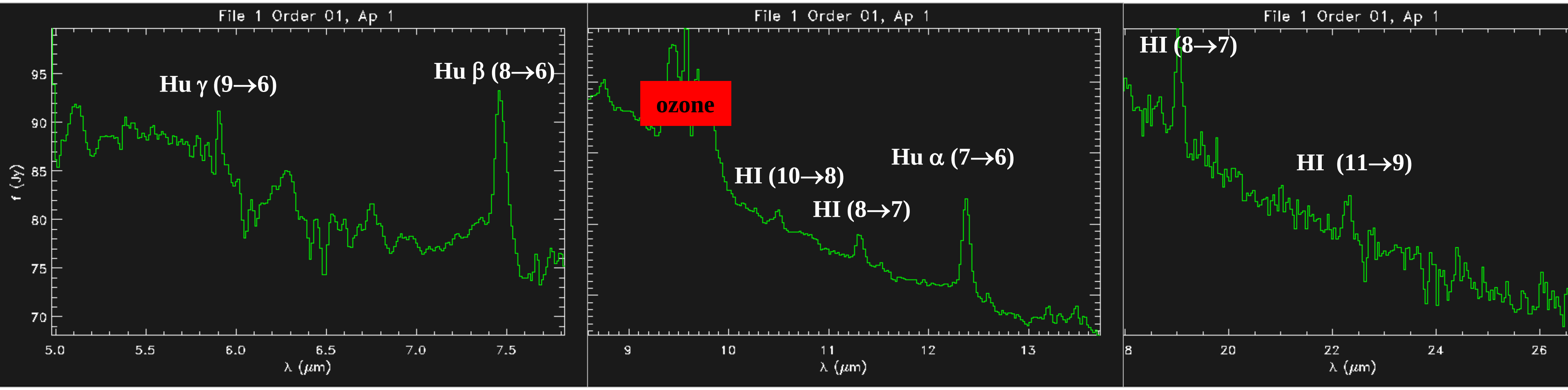
6/6/15 SOFIA FORCAST Grism Spectra of Nova Sgr 2015#2

V Light Curve ⇒



Uncalibrated 5-26.5 μm IR spectrum ~75 days post-maximum

⇓



- *Pure Hydrogen emission spectrum*
- *Metallic forbidden lines are quenched because of the the high shell density*

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*

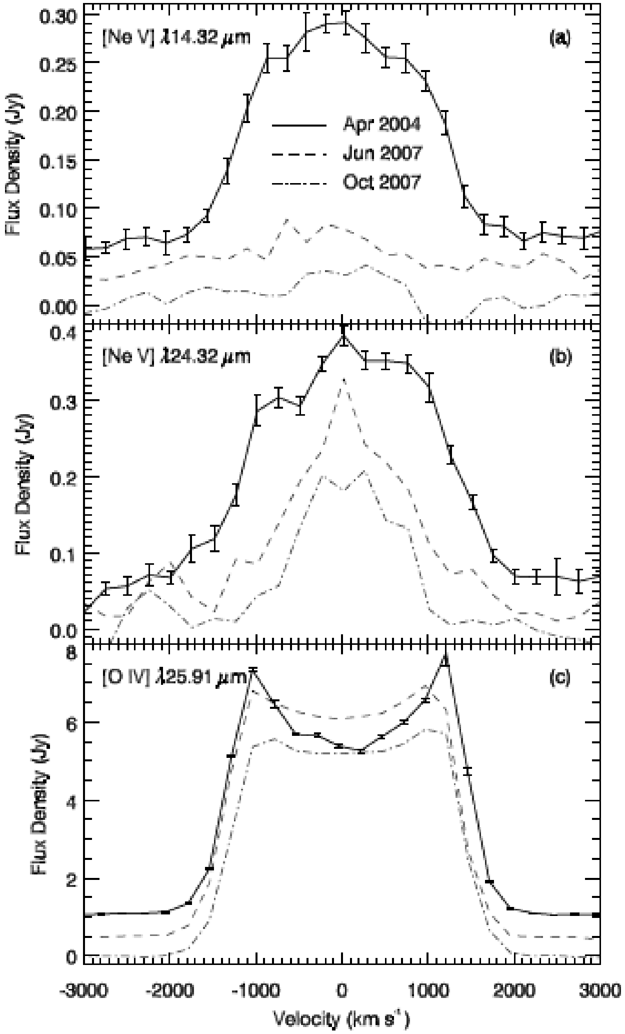
- *SOFIA can fly anywhere and any time to respond to transient events*

- *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)*

Backup

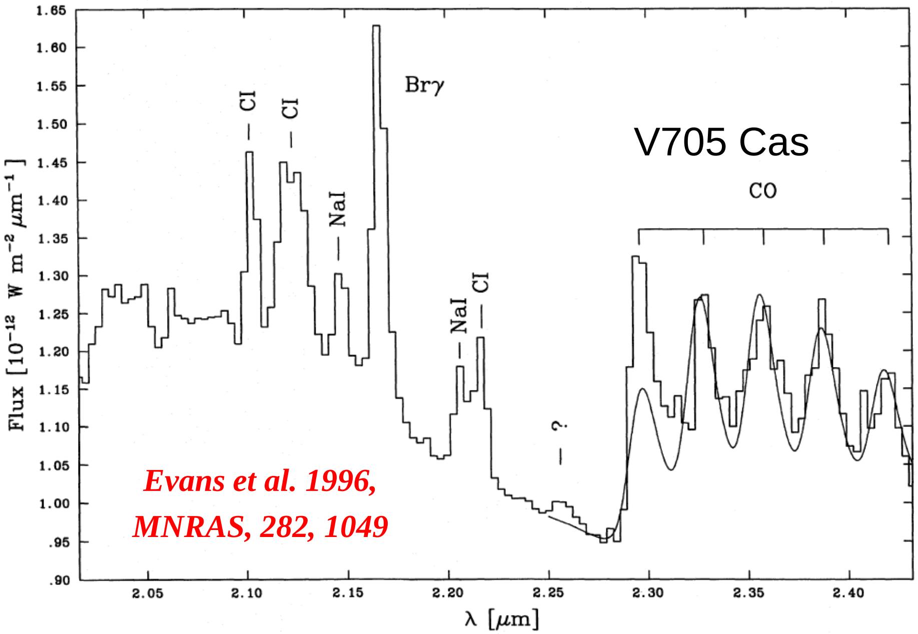
Velocity Resolved Spitzer Spectra:V1494 Aql

Line shapes reveal kinematic structure associated with different ionization potentials

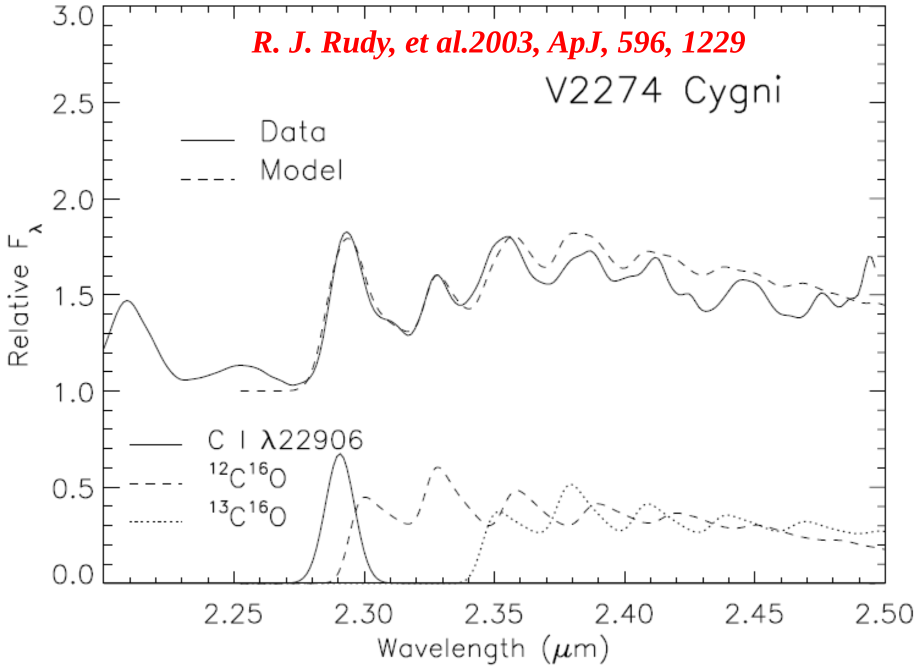


L. A. Helton, et al. 2012, ApJ, 755, 37

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



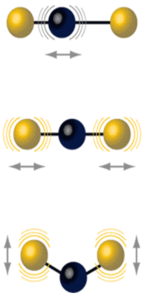
Evans et al. 1996, MNRAS, 282, 1049



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

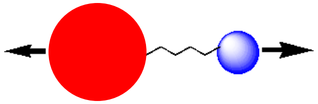
- *CO formation has been a precursor to dust production in a number of CO novae (e.g., NQ Vul, V705 Cas, V496 Sct, and V2676 Oph)*
- *The ^{12}C/^{13}C ratio can be used to test TNR models. ^{13}C was very overabundant in V2676 Oph and V2274 Cyg (factors of ~20 and ~90 respectively)*

IR Spectra of Dust Grains

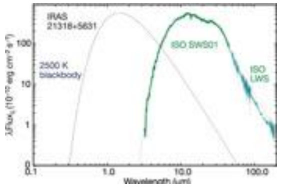


- ***Silicates: SiO_2 bond stretching and bending vibrational mode emission at 10 μm and 20 μm***

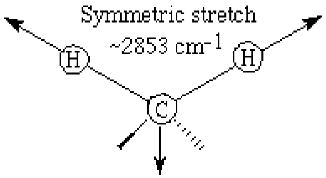
- ***Silicon Carbide: SiC stretching vibrational mode emission at 11.3 μm***

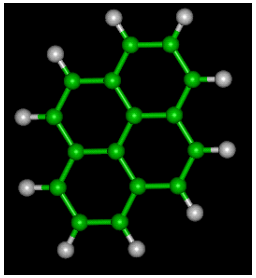


- ***Carbon and iron: Smooth emissivity***



- ***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***





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:***

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

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

Note that IR lines of [Na III] 7.32 μm, [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