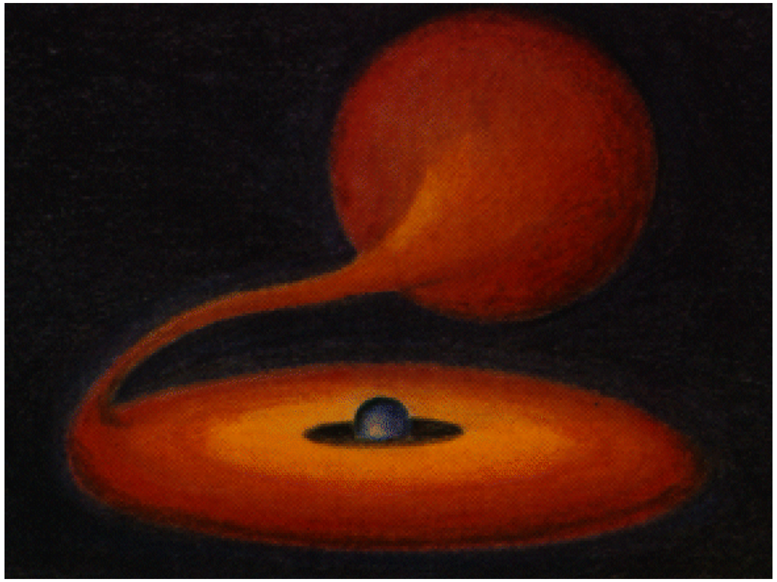
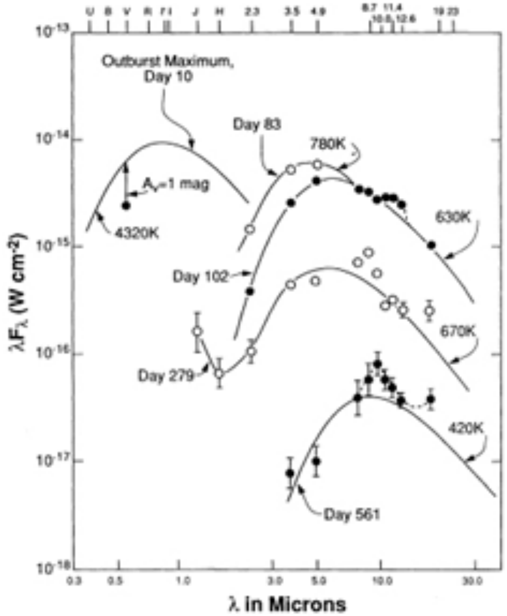
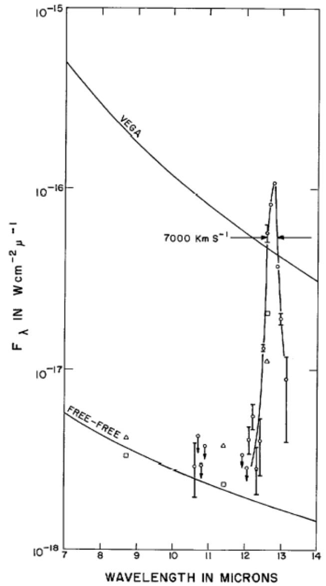
# *Observations of Novae in the Infrared*



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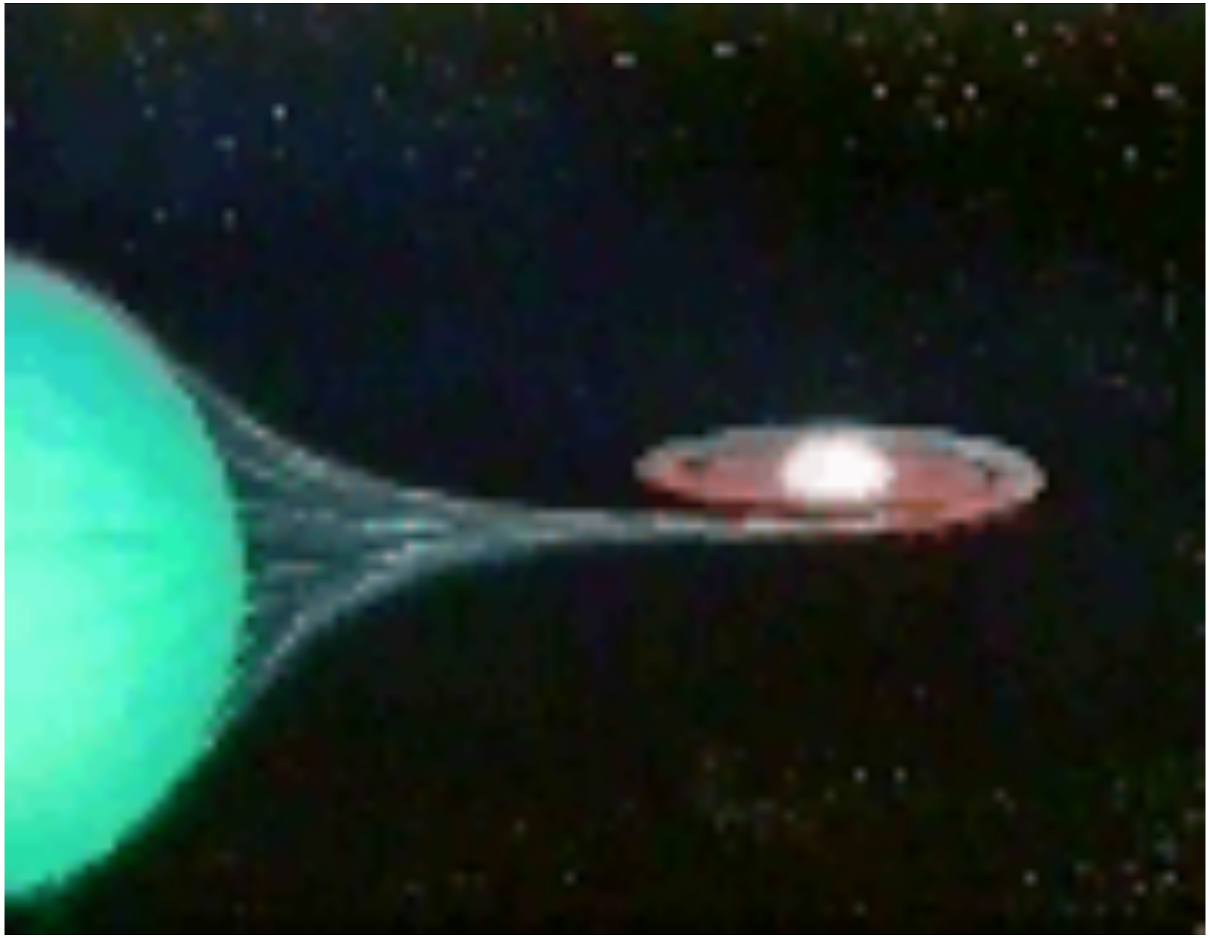
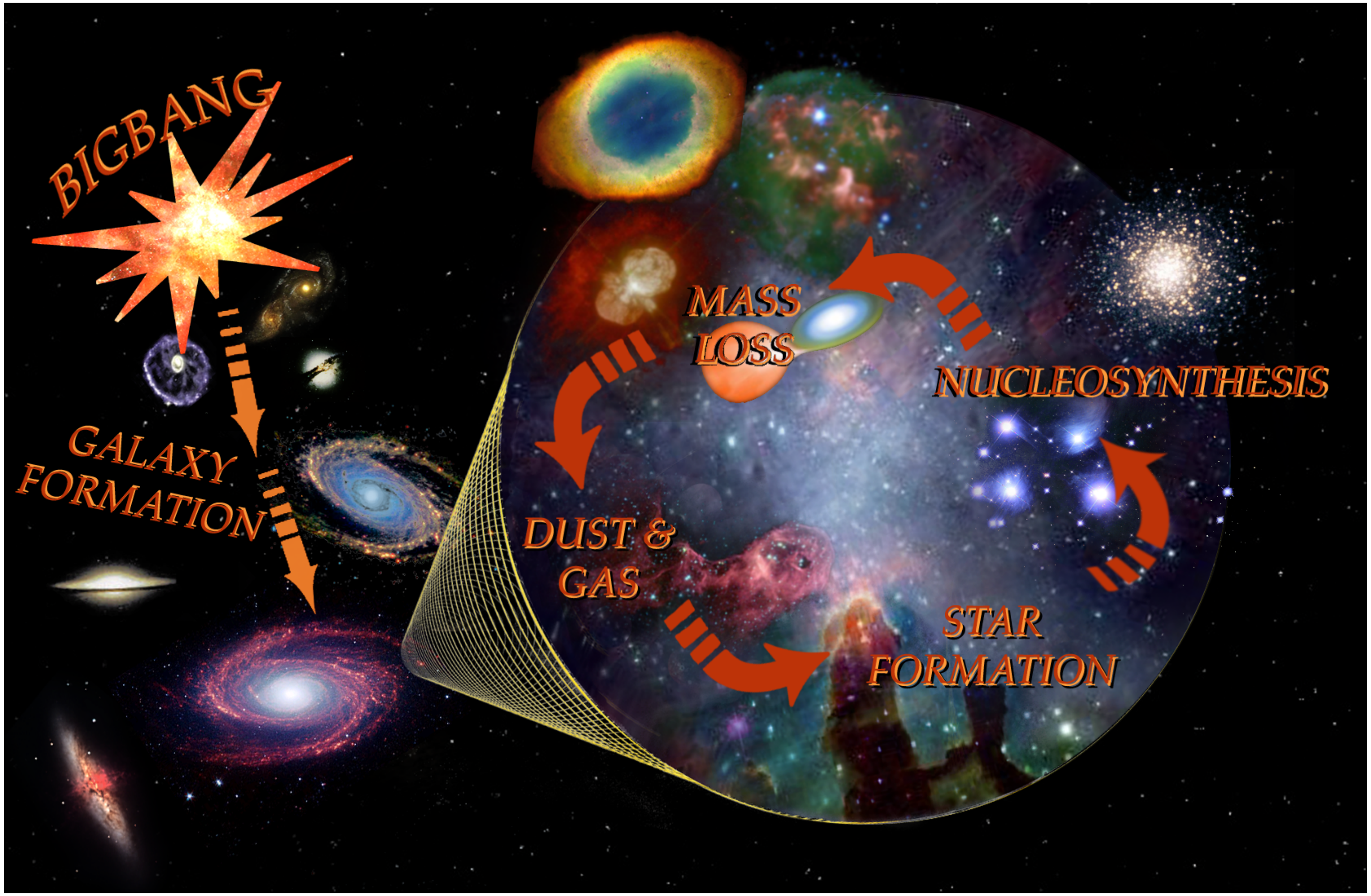
# *Outline*

- ***Novae and Galactic chemical evolution***
- ***Outburst Development in the IR***
- ***IR Observations of gas and grains in the ejecta***
- ***Nova grains in the primitive Solar System***
- ***Future observations with SOFIA and JWST***
- ***Summary***

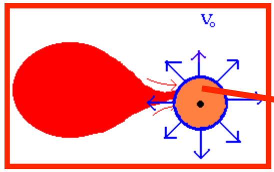
# *A Classical Nova Explosion: Accretion followed by a TNR*



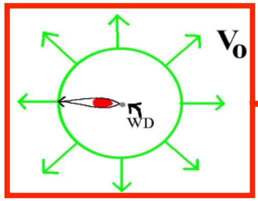
# *The Role of Classical Novae in Galactic Chemical Evolution*



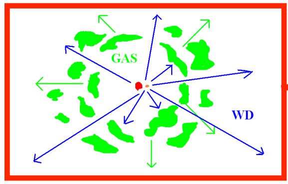
# *IR Development Phases*



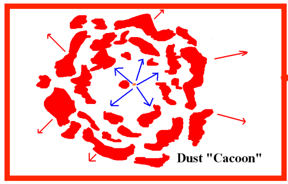

*Fireball Expansion Phase*



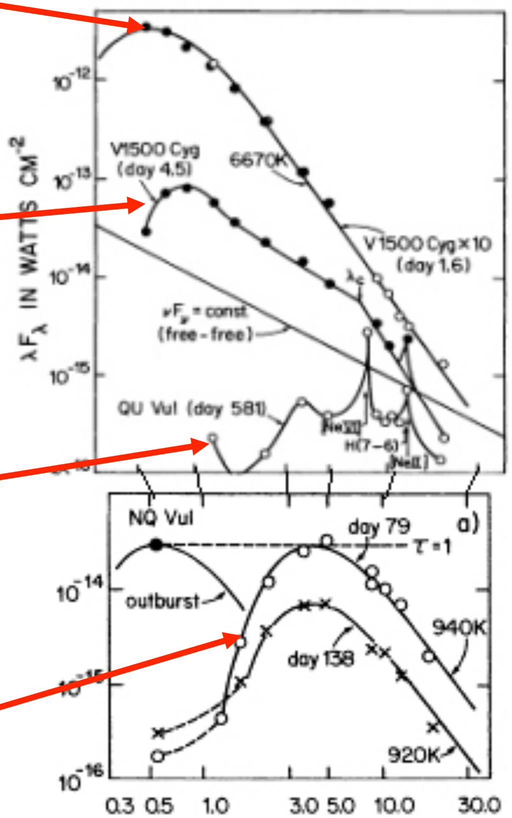

*Free-Free Expansion Phase*




*Coronal Phase in ONeMg Novae*




*Dust Cocoon Phase in CO Novae*

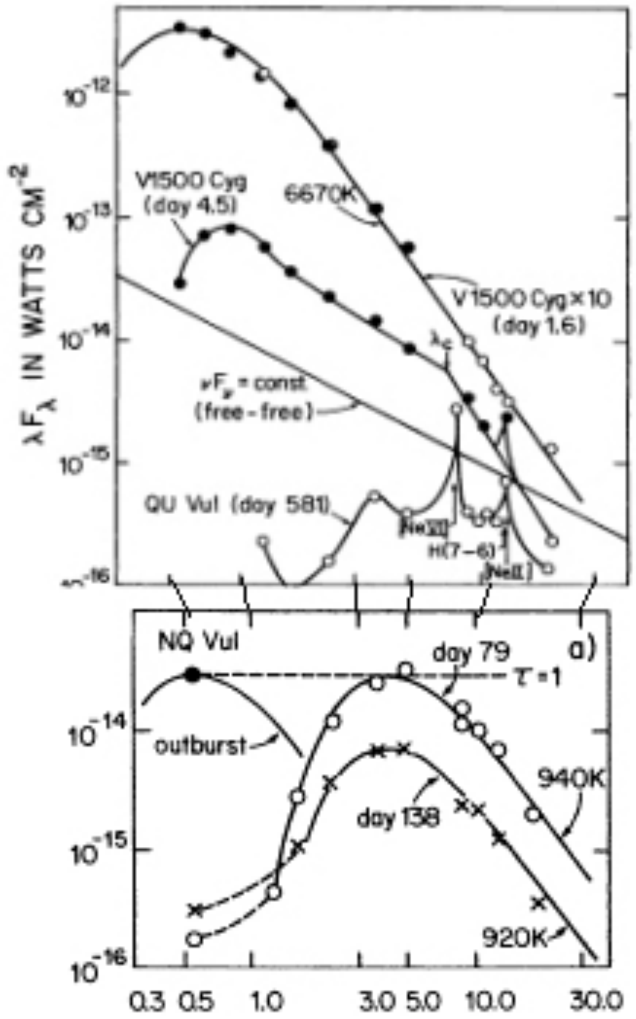



*λ in μm*

*R. D. Gehrz (1988, 1990)*

- ***The luminosity of the outburst fireball is $L_o \geq L_{Edd}$***
- ***$\lambda_c$ measures $n_H$ and the ejected ionized gas mass $M_{gas}$ during the free-free expansion phase***
- ***$L_o \geq L_{Edd} = L_{IR}$ for optically thick dust shells $\Rightarrow L_o$ = constant for a long time***

# *Physical Parameters Derivable from IR SED's and Spectra*




- ***$T_{BB}$ in K and time of the outburst $t_o$ in JD for expanding photospheres and dust shells***
- ***The apparent luminosity; for blackbodies, $f = 1.36\,(\lambda f_\lambda)_{max}$ in $W\ cm^{-2}$***
- ***The free-free self-absorption wavelength $\lambda_c$ in $\mu m$***
- ***The outflow velocity $V_o$ in $Km\ s^{-1}$ from emission lines***

# *Mass of the Ejecta from IR SED's*

- ***From Thomson scattering, which dominates the shell opacity during the fireball/free-free transition:***

$$M_{gas} \approx 3.3 \times 10^{-13} (V_o t)^2 \quad \textbf{in } M_\odot$$

- ***From $\lambda_c$ during the optically thin free-free phase:***

$$M_{gas} \approx 5 \times 10^{-14} (V_o t)^{5/2} \lambda_c^{-1} \quad \textbf{in } M_\odot$$

- $M_{gas} \approx$ ***1-3x10$^{-4}$ $M_\odot$ for ONeMg WD's***

- $M_{gas} \approx$ ***1-5x10$^{-5}$ $M_\odot$ for CO WD's***

***These methods are independent of D as long as $V_o$ is known from IR spectra***

# *Ejected Gas Mass Determination from IR/Radio Observations: Conclusions*

- ***Radio and IR observations give ejected masses of ionized gas that are consistent with one another***
- ***These masses are lower limits to the true ejected mass since the neutral gas is not observed***
- ***These lower limits are substantially larger than the ejected masses predicted by existing theoretical TNR models***
- ***The potential of Classical Novae for making significant contributions to ISM/Solar System abundances is therefore substantial and may have been underestimated***

# *Physical Parameters from IR/Radio SED's, Light Curves, and Direct Imaging*

- ***Angular radii of blackbody photospheres and shells:***

$$\theta_r \approx 10^{11} \sqrt{(\lambda f_\lambda)_{\max}}\, T_{BB}^{-2} \quad \textit{in arcseconds}$$

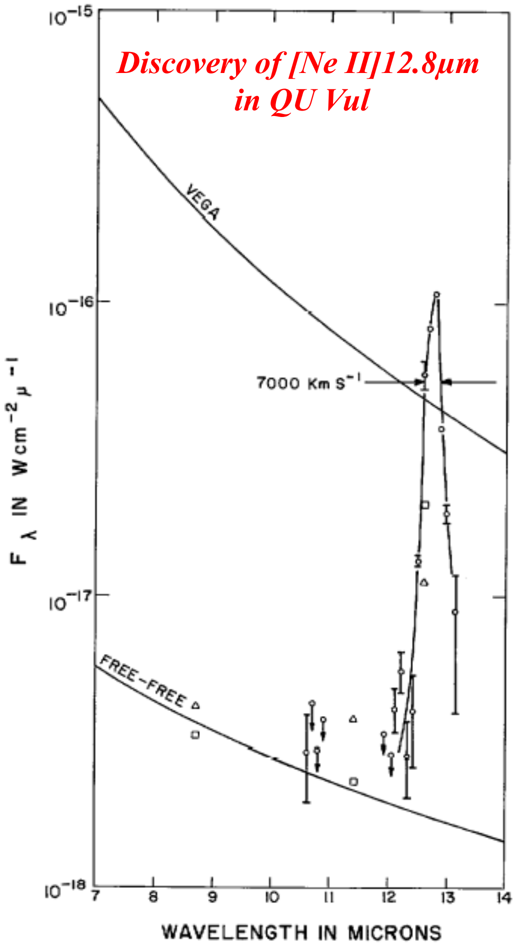
- ***Distance by blackbody and direct expansion parallaxes:***

$$D \approx 5.8 \times 10^{-7} V_o t \theta_r^{-1} \quad \textit{in kpc}$$

- ***The luminosity of the WD central engine given D:***

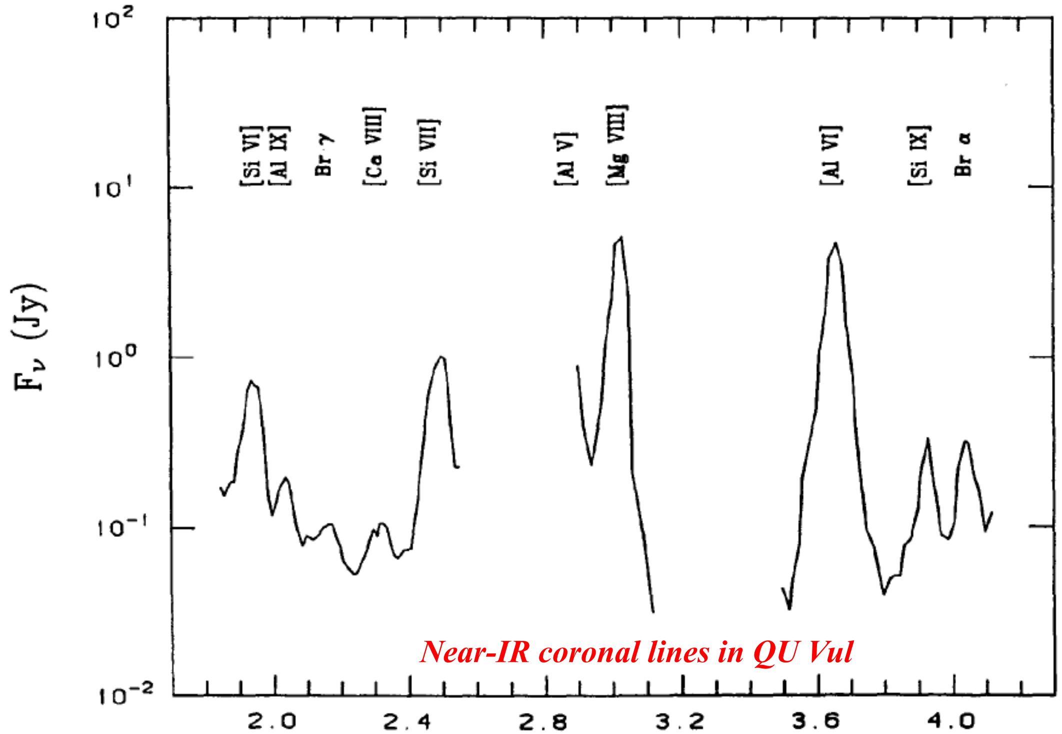
$$L_o \approx 3 \times 10^{17} D^2 (\lambda f_\lambda)_{\max} \quad \textit{in } L_\odot \quad (\textit{Note that } L_o \geq L_{Edd})$$

# *Abundances from IR Forbidden Emission Lines*



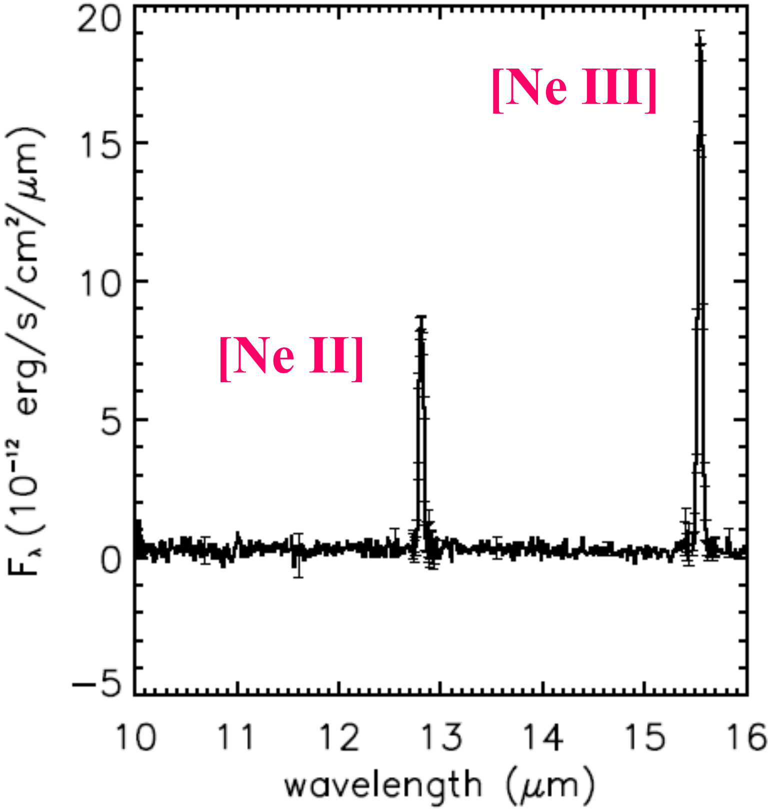

*Gehrz et al. 1985, ApJ, 298, L47*

## *QU Vul: a TNR on an ONeMg WD*

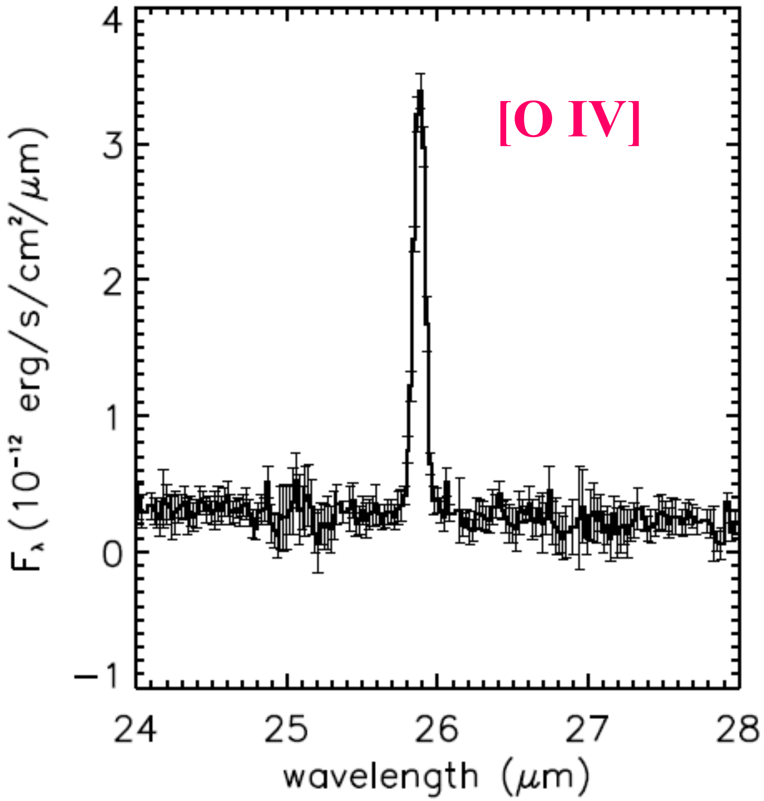



*Greenhouse et al. 1988, AJ, 95, 172*

# Spitzer IRS Spectra of Nova QU Vul 20 Years after Outburst




*IRS Short-High*

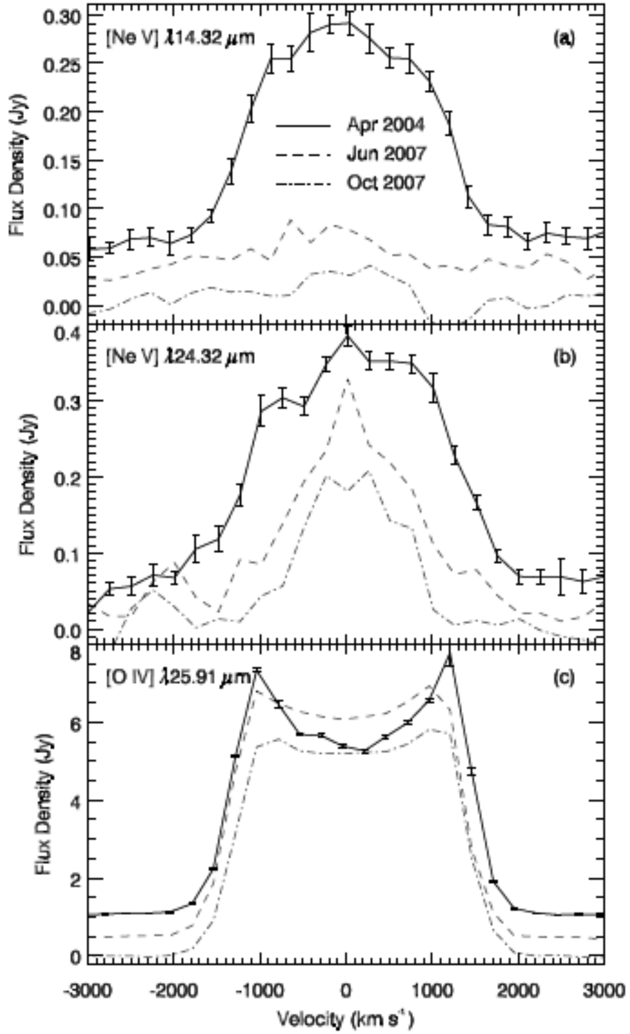



*IRS Long-High*

*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*

# *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 :***

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

$$^{26}Mg \text{ via:} \quad ^{26}Al \rightarrow {}^{26}Mg + e^{+} + \nu \qquad (\tau_{1/2} = 7 \times 10^{5} \text{ yr})$$

# *Classical Novae and Abundance Anomalies*

***Gehrz, Truran, and Williams 1993 (PPIII, p. 75) and Gehrz, Truran, Williams, and Starrfield 1997 (PASP, 110, 3) have concluded that novae may affect ISM abundances:***

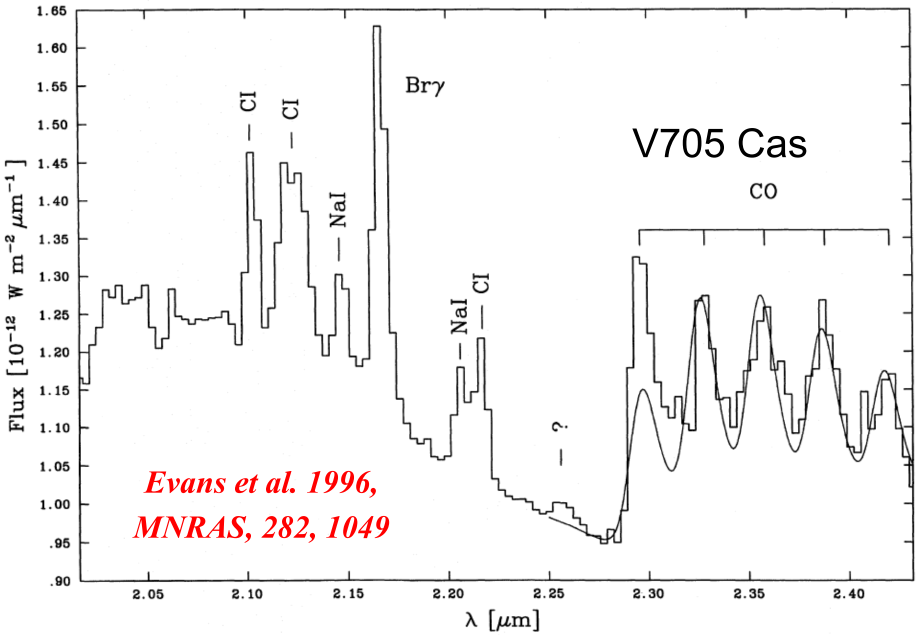
- ***Novae process ≈ 0.3% of the ISM***
- $(dM/dt)_{novae} \approx 7\text{x}10^{-3}\ M_{\odot}\ yr^{-1}$
- $(dM/dt)_{supernovae} \approx 6\text{x}10^{-2}\ M_{\odot}\ yr^{-1}$

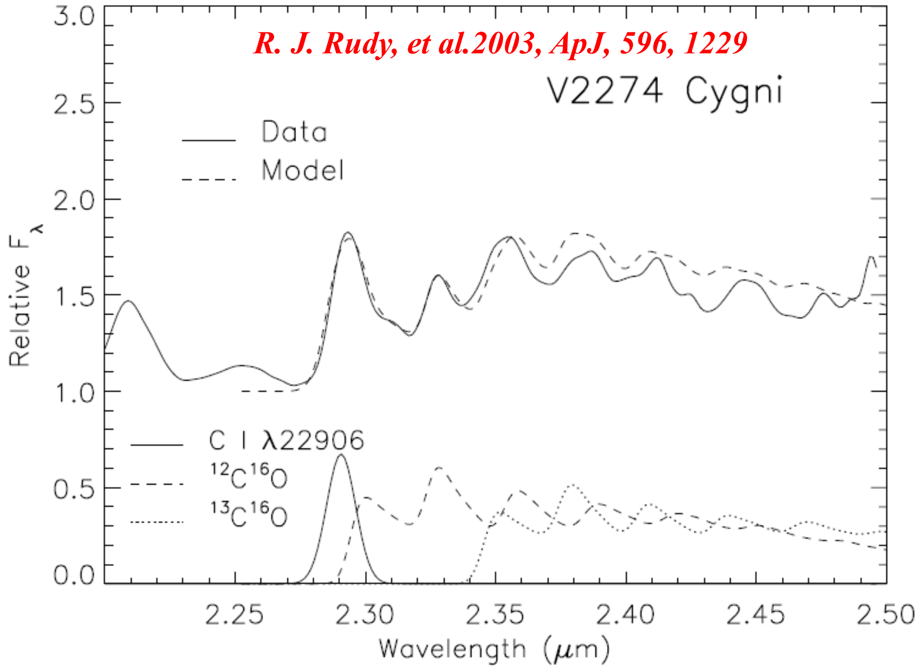
***Novae may be important on a global Galactic scale if they produce isotopic abundances that are ≥ 10 times SN and ≥ 100 times Solar; Ejected Masses calculated from IR/Radio methods give a lower limit (not all the lines from all ionization states can be observed)***

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

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

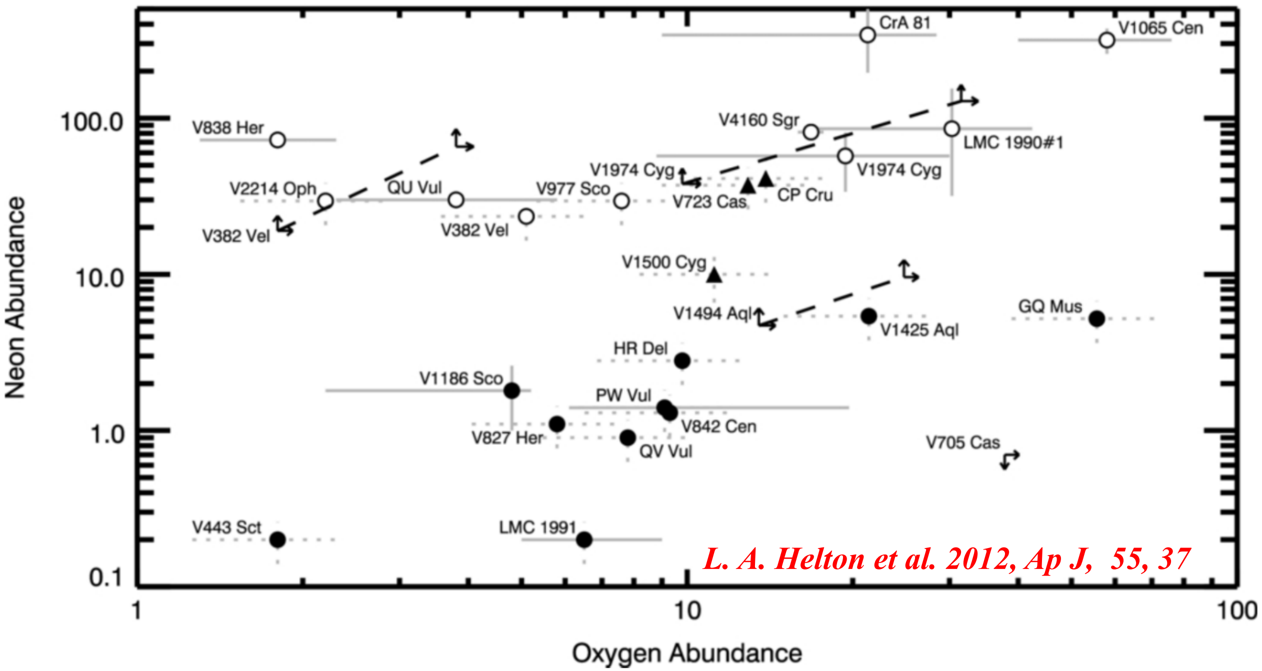
# *Molecular Emission in CNe and the $^{12}C/^{13}C$ Ratio*

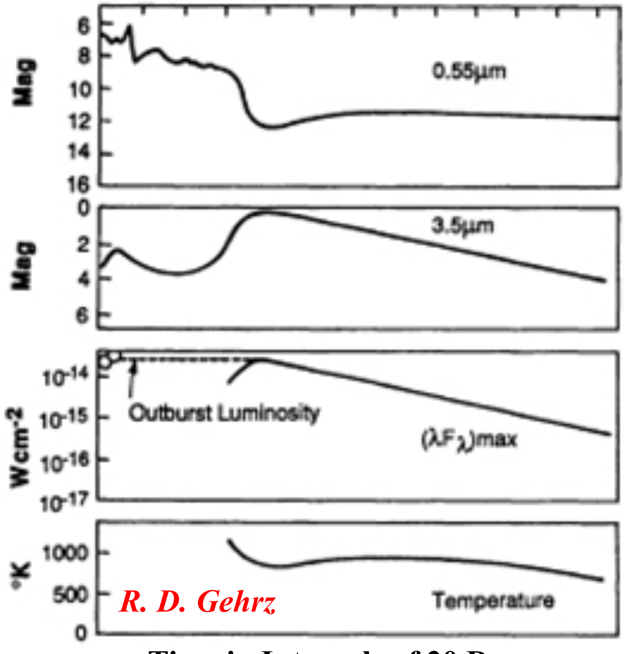



- ***V705 Cas: No conclusive evidence for $^{13}C^{16}O$ and $^{12}C/^{13}C \geq 5$***
- ***V2274 Cyg: Both $^{12}C/^{16}O$ and $^{13}C/^{16}O$ required to fit the band heads: $^{12}C/^{13}C < 1.2$, Solar value is 91 implying that $^{13}C$ is very overabundant***

# Dust Condensation in CO Novae



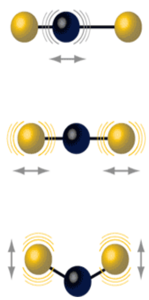

$$T_c \approx 1000\ K$$

$$L_o \approx L_{Eddington}$$

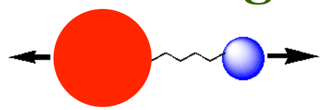
$$R_c = \left[ \frac{L_o}{16\pi\sigma T_c^4} \right]^{1/2}$$

$$t_c \approx \frac{R_c}{V_o}$$

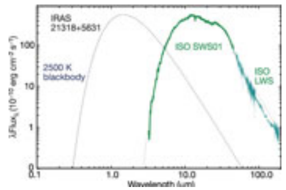
# *IR Spectra of Dust Grains: Molecular Structure*



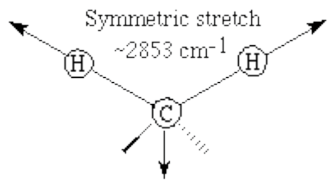
- *Silicates: $SiO_2$ bond stretching and bending vibrational mode emission at 10 μm and 20 μm*
- *Silicon Carbide: SiC stretching vibrational mode emission at 11.3 μm*

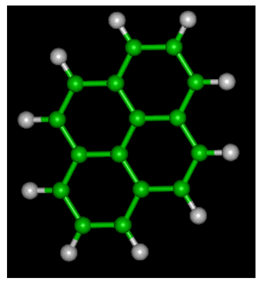


- *Carbon and iron: Smooth emissivity*



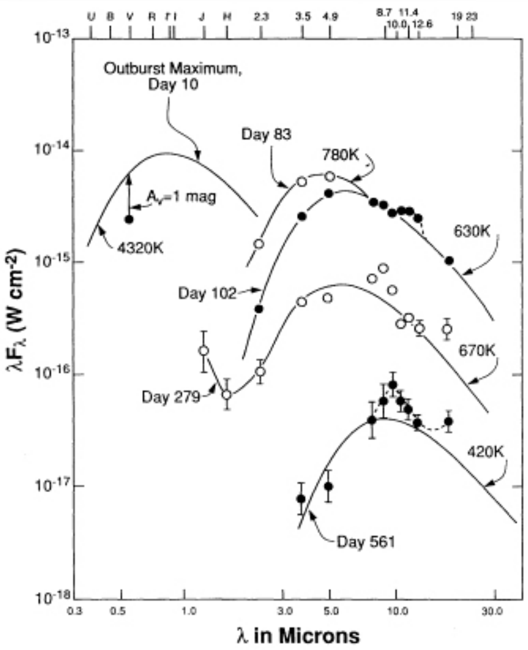

- *Hydrocarbons (HAC and PAH): C-H stretching and bending at 3.3 μm, C-C stretching modes at 6 - 18 μm, drumhead modes at longer wavelengths*

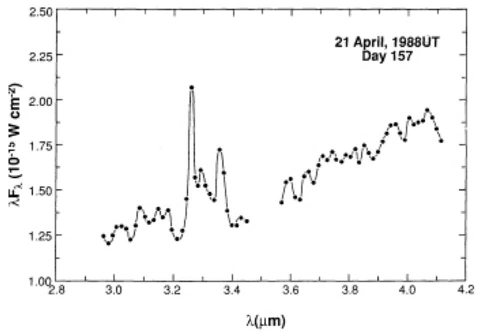


# *Nova Grain Properties*

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

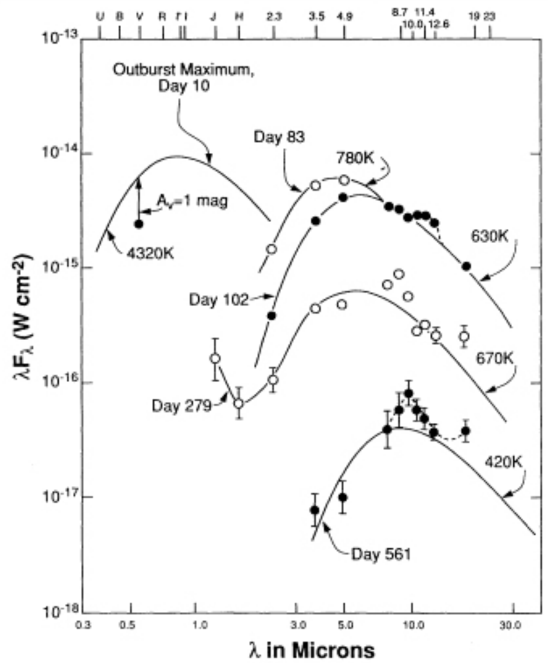


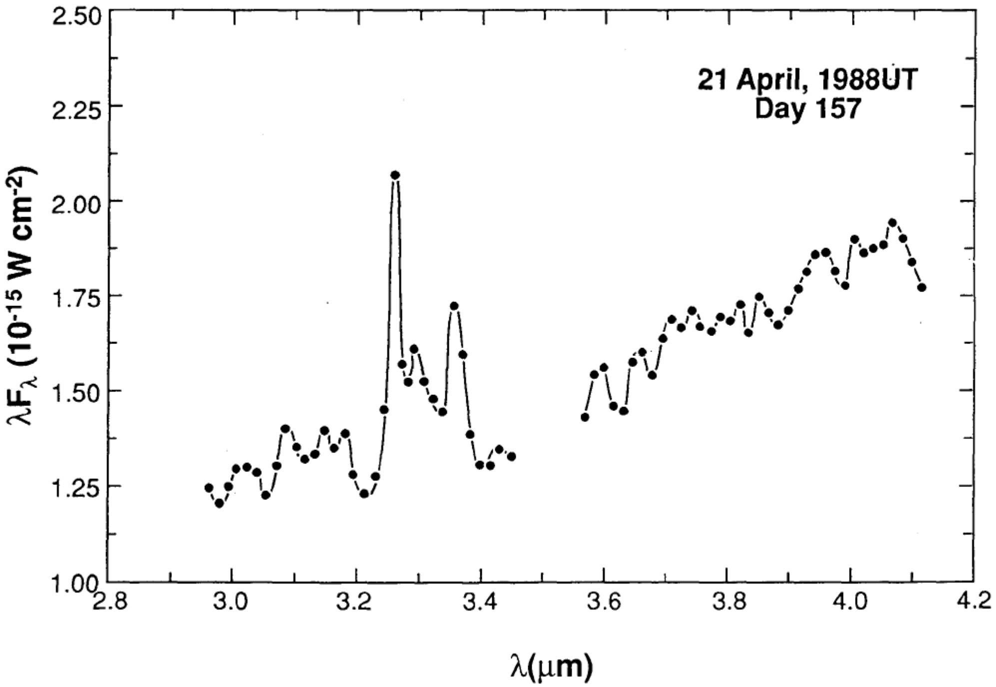




- ***A small fraction (≤ 20%) of classical novae form dust***
- ***Novae produce carbon, SiC, silicates, and hydrocarbons***
- ***Abundances can be derived from visual opacity, IR opacity, and IR emission feature strengths***
- ***The grains grow to radii of 0.2-0.7μm***

# *Grain Condensation in Nova QV Vul 1987 (2)*

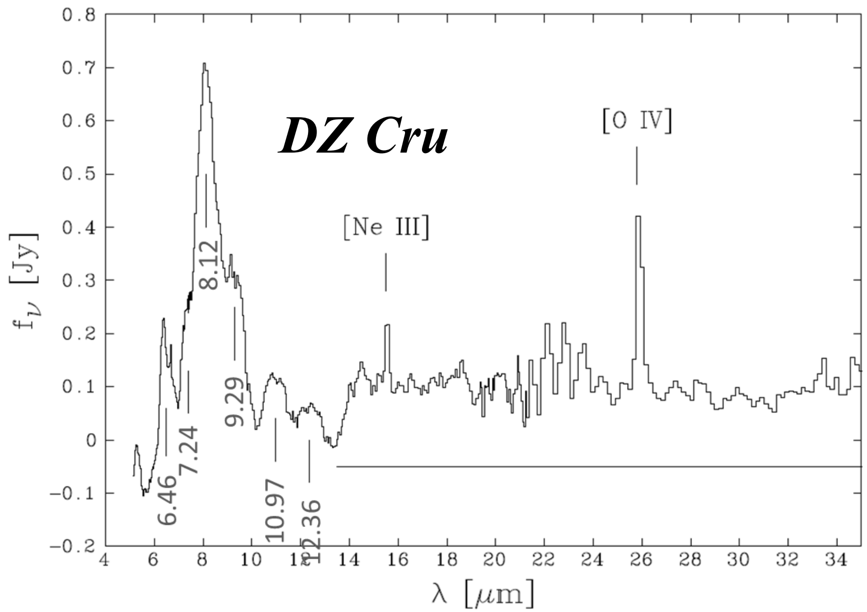
Gehrz et al. 1992 (Ap. J., 40, 671)



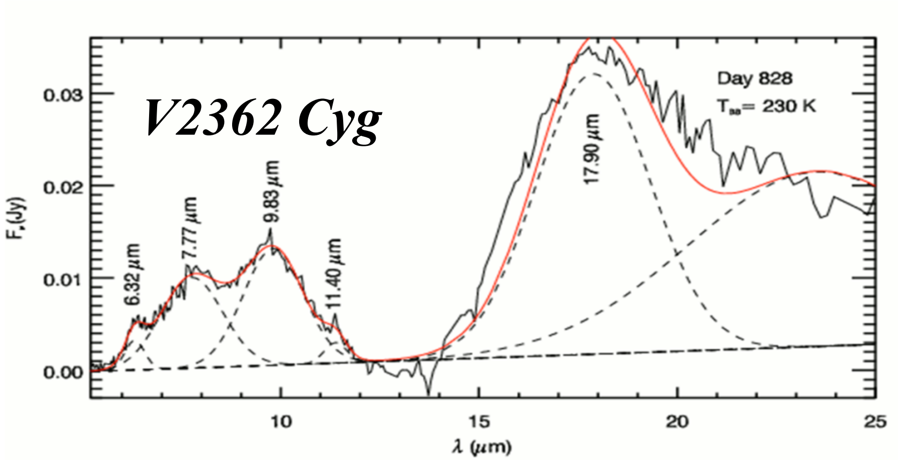




- *Carbon, Silicates, SiC, and PAH grains formed at different epochs suggesting abundance gradients in the ejecta.*
- *A. D. Scott (2000, MNRAS, 313, 775-782) has shown that this could be explained by an asymmetric ejection due to a TNR on a rotating WD*

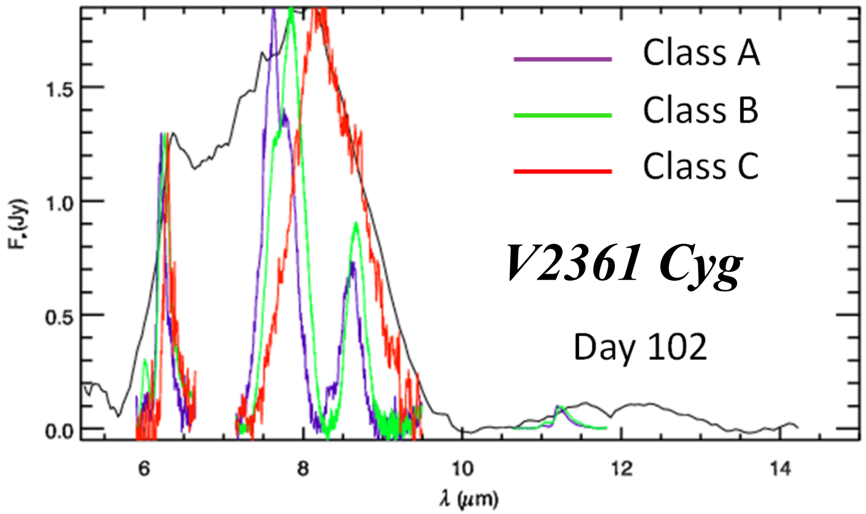
# *Spitzer Spectra of Hydrocarbon Grains in CNe*




*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*

# *Grain Mass, Abundance, and Size*

- ***$M_{dust}$ from the infrared luminosity of the dust shell:***

$$M_{dust} \approx 1.6 \times 10^{-11} \rho_{grain} V_o^2 t^2 T_{BB}^{-6}$$ ***in $M_\odot$***

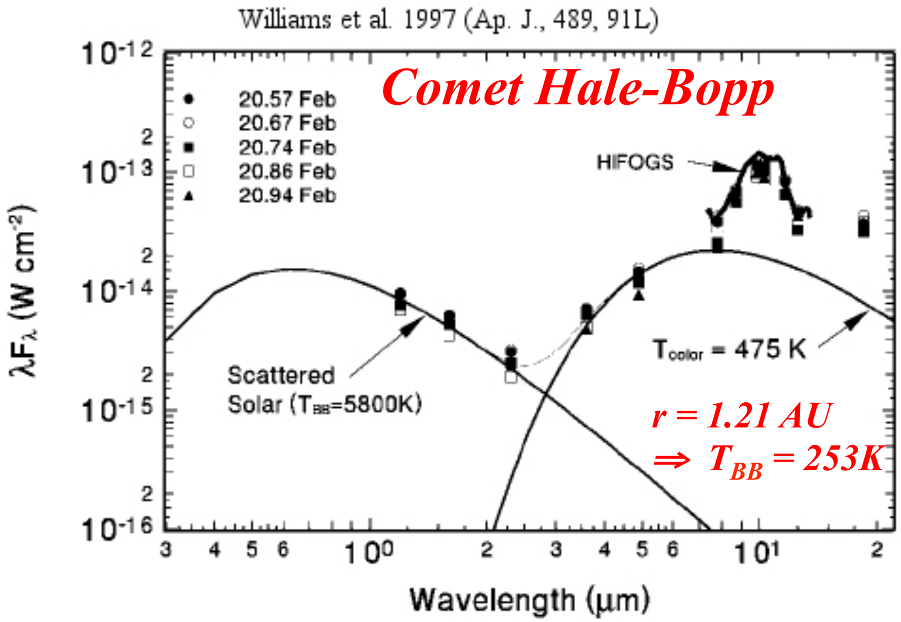
- ***Abundance of the grain condensables is given by:***

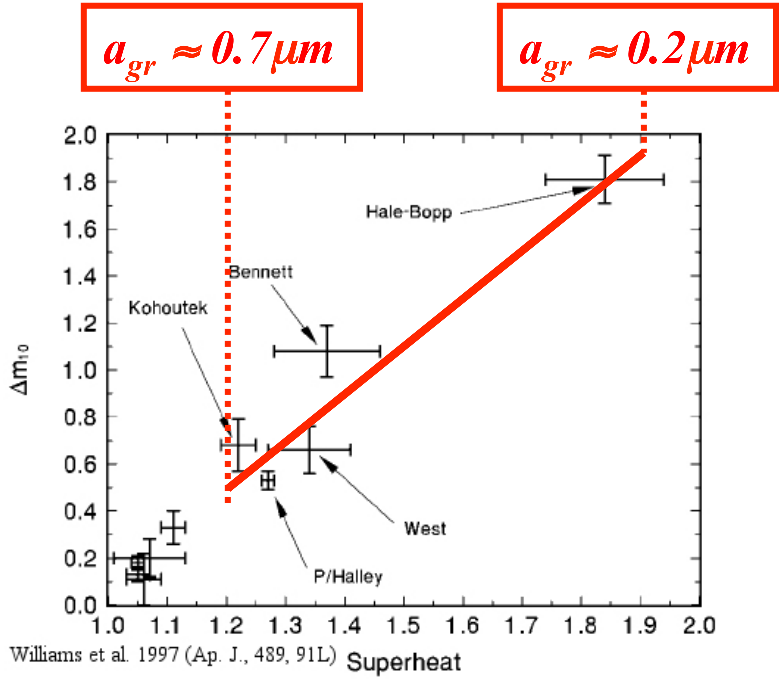
$$M_{dust} / M_{gas}$$ ***compared to solar abundance***

- ***Grain radius from the optical depth of the visual transition and $L_{IR}$:***

$$a_{gr} \approx 2 \times 10^{22} L_o V_o^{-2} t^{-2} T_{BB}^{-6}$$ ***in μm*** ***($a_{gr} \approx$ 0.2-0.7μm)***

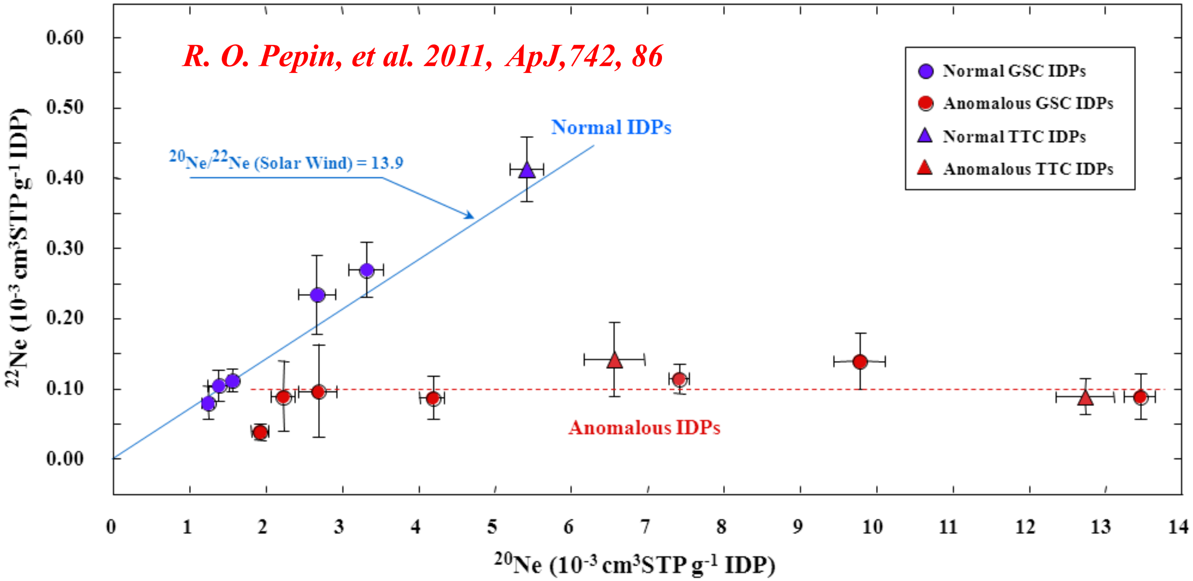
# *Comet Dust and Nova Dust Compared*

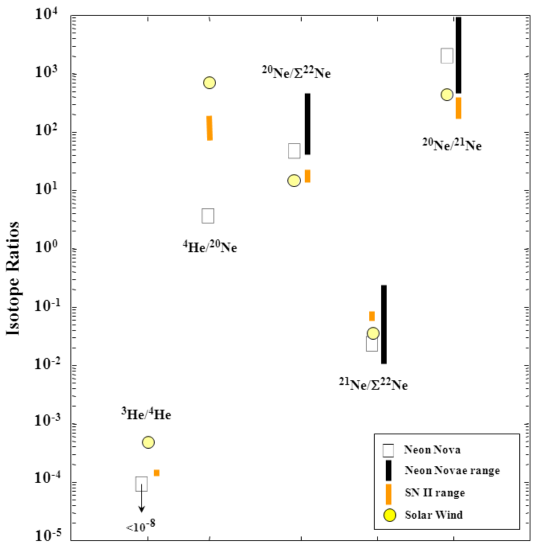


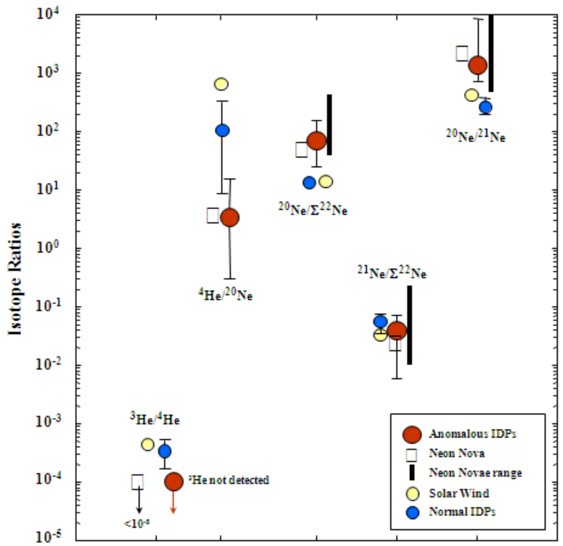




- *Both Comet dust and nova dust contain silicates, carbon, and hydrocarbons*
- *Comets have coma emission dominated by grains the size of those produced in nova outflows*

# *Comet Grains Produced in a Neon Nova?*



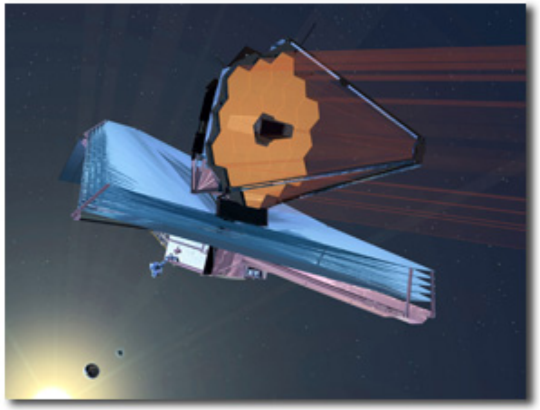




- ***IDP's collected in the stratosphere from comets Grigg-Skjellerup and Tempel-Tuttle during perihelion passage show anomalous neon isotope ratios***
- ***$^3He/^4He$ ratios confirm that these grains have not received substantial solar wind exposure***
- ***The neon isotope ratios are consistent with yields predicted by models of ONe nova TNRs rather than models of SN II***

# *Future Nova Research from the Air and in Space*

- ***Stratospheric Observatory for Infrared Astronomy (SOFIA)***
  - *2.5-m clear aperture airborne telescope flying at 45,000 feet altitude*
  - *0.3 – 240 μm with spectral resolutions from R = λ/Δλ = 200 to 3,000*
  - *Covers all wavelengths and spectral resolutions needed to study nova dust mineralogy and abundances from IR forbidden emission lines*


- ***James Webb Space Telescope (JWST)***
  - *~ 6.5-m aperture 30K telescope orbiting at L2*
  - *0.6 – 28 μm with spectral resolutions from R = λ/Δλ = 100 to 3,000*
  - *Ideal for studies of extragalactic novae*



# Milestones in Flight History
# Dryden Flight Research Center

NASA

## SOFIA

**NASA's flying observatory resumes test flights including the first in-flight opening of the telescope cavity door.**

**December 9, 2009**

# *Summary and Conclusions*

- *IR/Radio data yield quantitative estimates for physical parameters characterizing the nova outburst: D , $L_o$ , $M_{gas}$ , $T_{dust}$ , $a_{dust}$ , $M_{dust}$ , $V_o$ , $L_o$ , grain composition, and elemental abundances*

- *Nova ejecta produce all known types of astrophysical grains: amorphous carbon, SiC, hydrocarbons, and silicates. Some nova grains may have made their way into the primitive Solar System.*

- *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 novae from the air and in space with SOFIA and JWST are promising*

# *Backup*

# *IR/Radio Observations of Classical Novae: Collaborators*

- ***University of Minnesota:** R. D. Gehrz, T. J. Jones, T. Harrison, A. Helton., J. Lyke, C. G. Mason, E. P. Ney, M. Schuster, C. E.Woodward*
- ***Cornell University:** T. Hayward, J. R. Houck, J. Miles*
- ***Caltech:** K. Matthews, G. Neugebauer, K. Sellgren*
- ***University of Wyoming:** G. Grasdalen, J. Hackwell*
- ***UK and Europe:** M. Barlow, A. Evans, J. Krautter, A. Salama*
- ***Additional Collaborators:** M. Greenhouse (GSFC), R. M. Hjellming (NRAO), S. G. Starrfield (AZ State), J. Truran (Chicago), R. E. Williams (STScI), A. F. Bentley (Eastern Montana), D. H. Wooden (NASA ARC), F. C. Witteborn (NASA ARC), S. A. Sandford (NASA ARC), L. J. Allamandola (NASA ARC), J. D. Bregman (NASA ARC), M. Klapisch (NRL), S. N. Shore (Pisa), R. M. Wagner (LBTO), G. Schwarz (AAS), D. Lynch (Aerospace), R. Rudy (Aerospace), A. R. Taylor (Calgary), E. R. Seaquist (Toronto)*

# *Ejected Mass from Modeling Radio Data*

- ***The data are best fit by a "Hubble flow" (V deceases linearly as a function of depth in the ejecta) in an optically thin free-free shell***

- ***This leads to a $\rho \propto r^{-3}$ density distribution from which a shell mass can be determined given D and V(r)***

Hjellming et al. 1979, AJ, 84, 1619

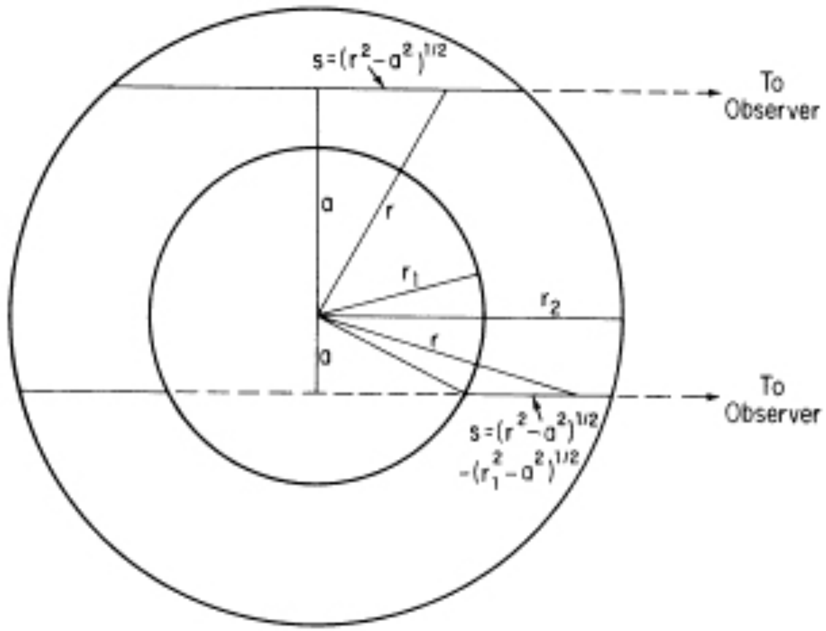



FIG. 2. The spherically symmetric shell geometry used for the nova models with lines of sight to an observer shown for the two cases for which the equation of transfer is integrated.

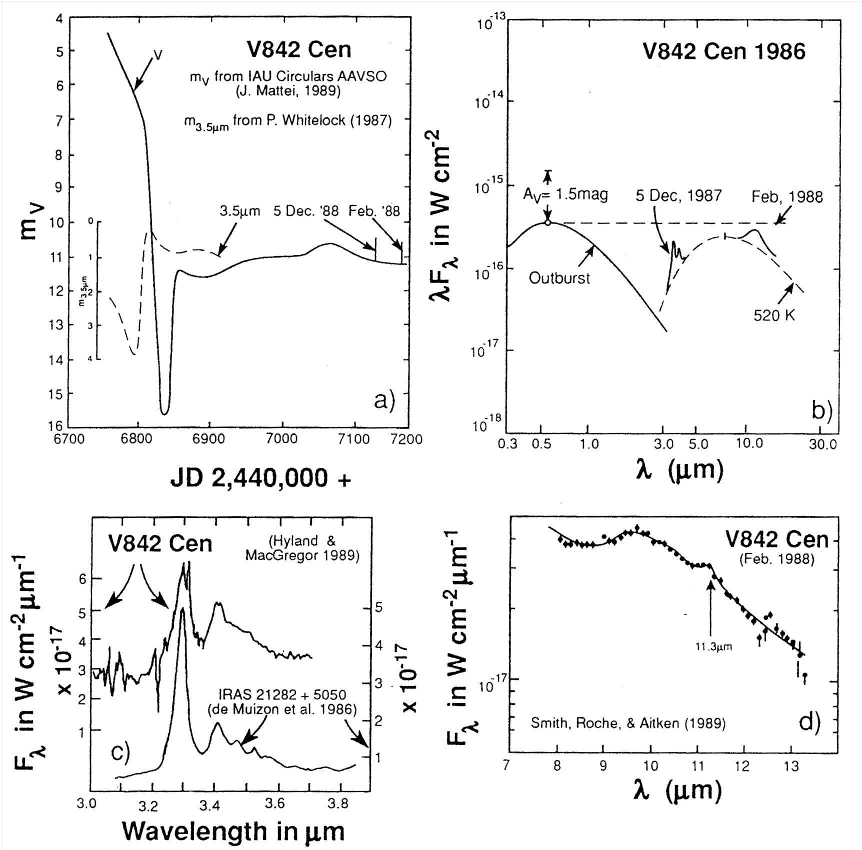
# *Chemical Abundances in Classical Novae from IR Data (1)*

| *Nova* | *X* | *Y* | $(n_X/n_Y)_{nova}$ <br> $(n_X/n_Y)_{\odot}$ | *Reference* |
|---|---|---|---|---|
| *LW Ser* | *Carbon dust* | *H* | ≥ 15 | *Gehrz et al. 1980a* |
| *QU Vul* | *Al* | *Si* | 70 | *Greenhouse et al. 1988* |
| *V1974 Cyg* | *Ne* | *Si* | ≈ 35 | *Gehrz et al. 1994* |
| *V705 Cas* | *Silicates* | *H* | ≥ 17 | *Gehrz et al. 1995a* |
| *V1974 Cyg* | *N* | *H* | ≈ 50 | *Hayward et al. 1996* |
| *V1974 Cyg* | *O* | *H* | ≈ 25 | *Hayward et al. 1996* |
| *V1974 Cyg* | *Ne* | *H* | ≈ 50 | *Hayward et al. 1996* |
| *V705 Cas* | *Ca* | *H* | 20 | *Salama et al. 1997 (ISO)* |
| *V705 Cas* | *O* | *H* | ≥ 25 | *Salama et al. 1997 (ISO)* |

# *Chemical Abundances in Classical Novae from IR Data (2)*

| *Nova* | *X* | *Y* | $(n_X/n_Y)_{nova}$ / $(n_X/n_Y)_{\odot}$ | *Reference* |
|---|---|---|---|---|
| *V705 Cas* | *Carbon dust* | *H* | ≈ 20 | *Mason et al. 1998* |
| *V1425 Aql* | *N* | *He* | ≈ 100 | *Lyke et al. 2002 (ISO)* |
| *CP Cru* | *N* | *H* | 75 | *Lyke et al. 2003 (ISO)* |
| *CP Cru* | *O* | *H* | 17 | *Lyke et al. 2003 (ISO)* |
| *CP Cru* | *Ne* | *H* | 27 | *Lyke et al. 2003 (ISO)* |
| *QU Vul* | *Ne* | *H* | ≥ 168 | *Gehrz et al. 2008 (Spitzer)* |
| *QU Vul* | *O* | *H* | ≥ 2.3 | *Gehrz et al. 2008 (Spitzer)* |

# *Grain Condensation in V842 Cen (1986)*




- ***Amorphous Carbon***
- ***Hydrocarbons***
- ***Silicates***

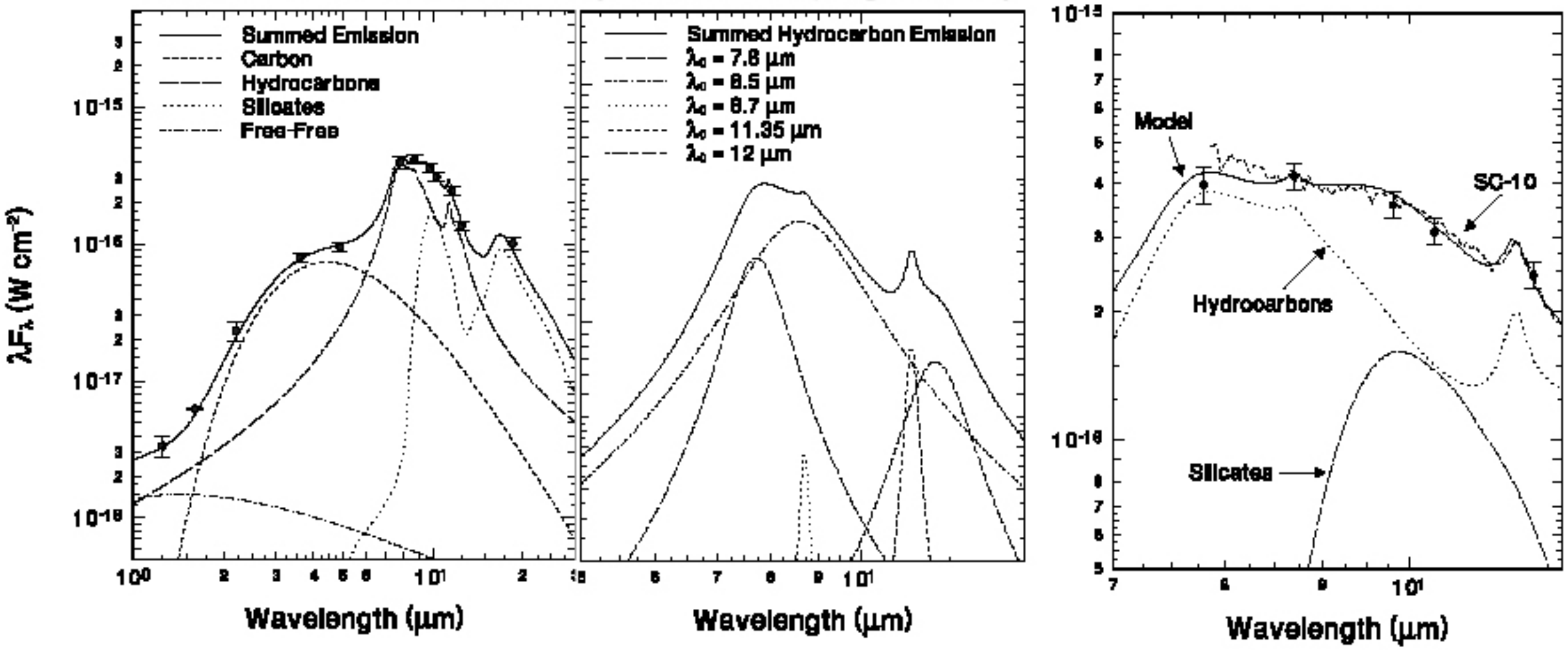
*From R. D. Gehrz, 1990, in Physics of Classical Novae, eds. A. Cassatella and R. Viotti, Springer-Verlag: Berlin, p. 138.*

# *Grain Condensation in V705 Cas (1993)*

INFRARED DEVELOPMENT OF V705 CASSIOPEIAE

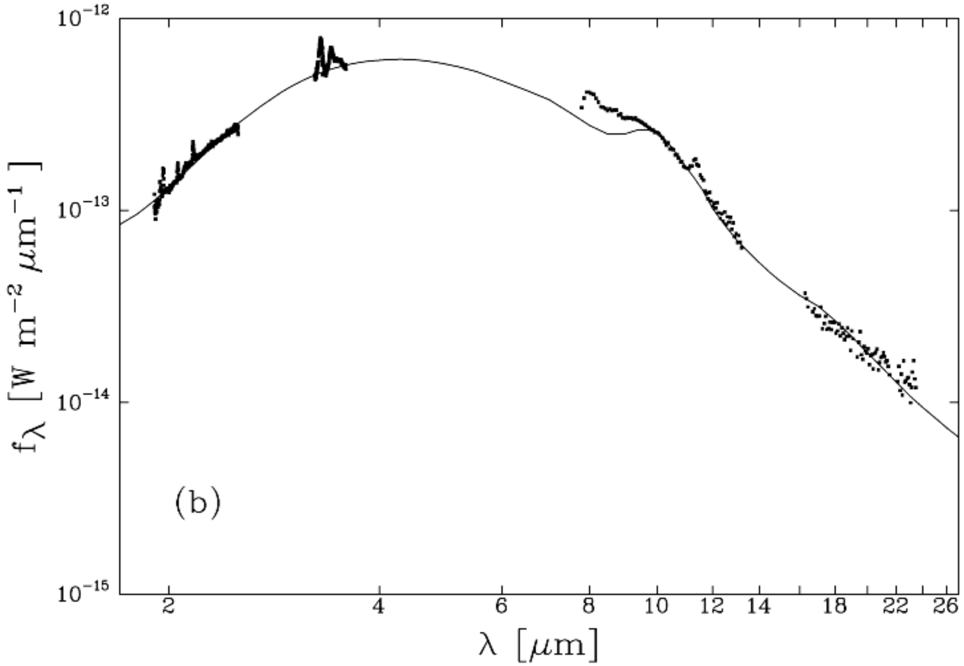
Mason et al. 1998 (Ap. J., 494, 783)

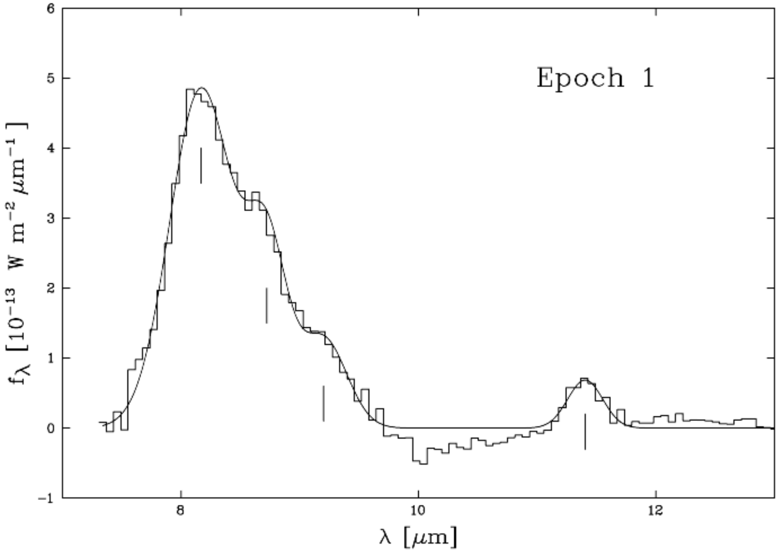
Day 373.5 1.2–18.5 μm photometry.




***Free-free, amorphous carbon, silicates, and hydrocarbon UIR emission are required to fit the IR spectrum in detail.***

# UIR Hydrocarbon Emission in V705 Cas

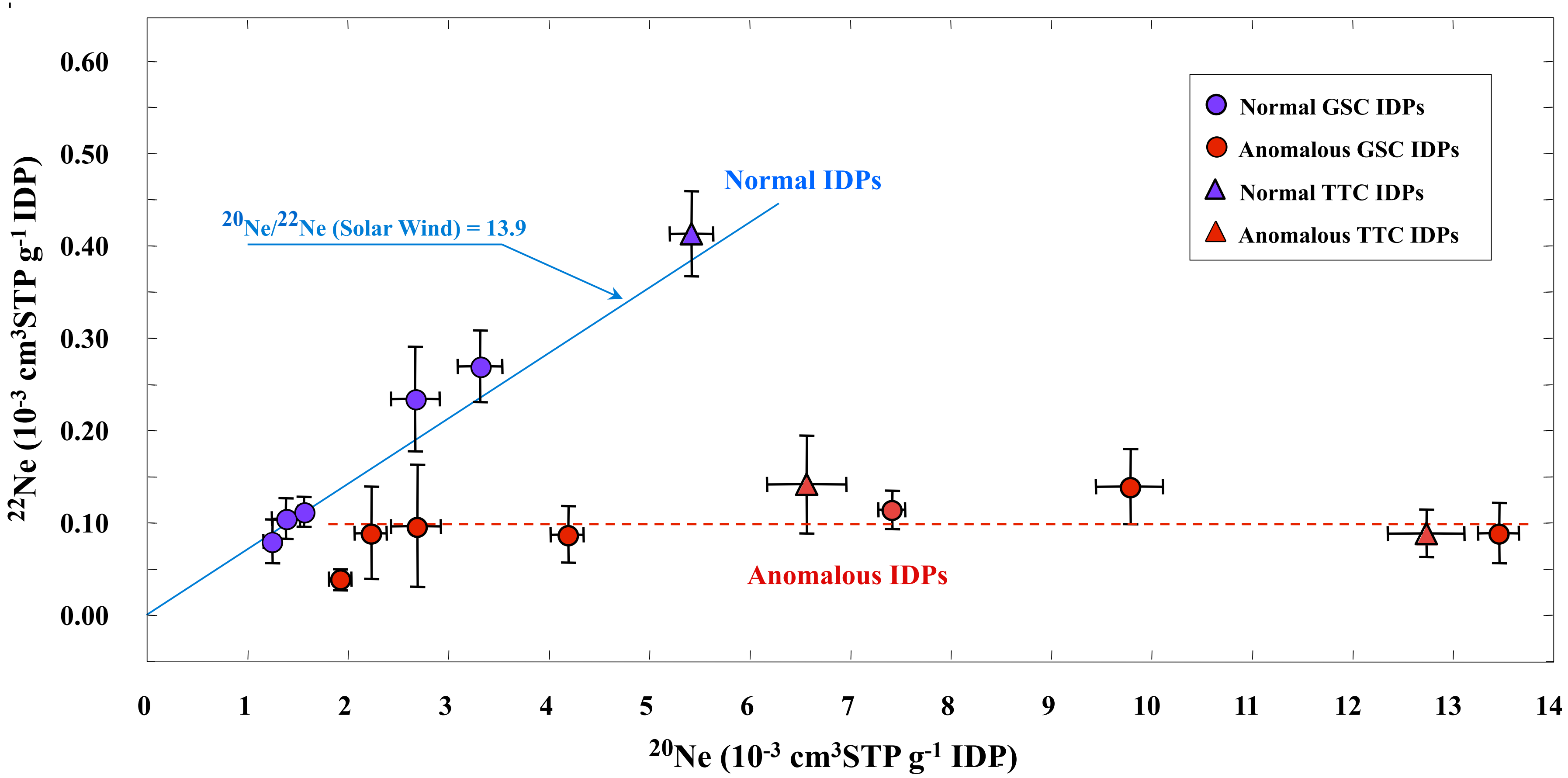


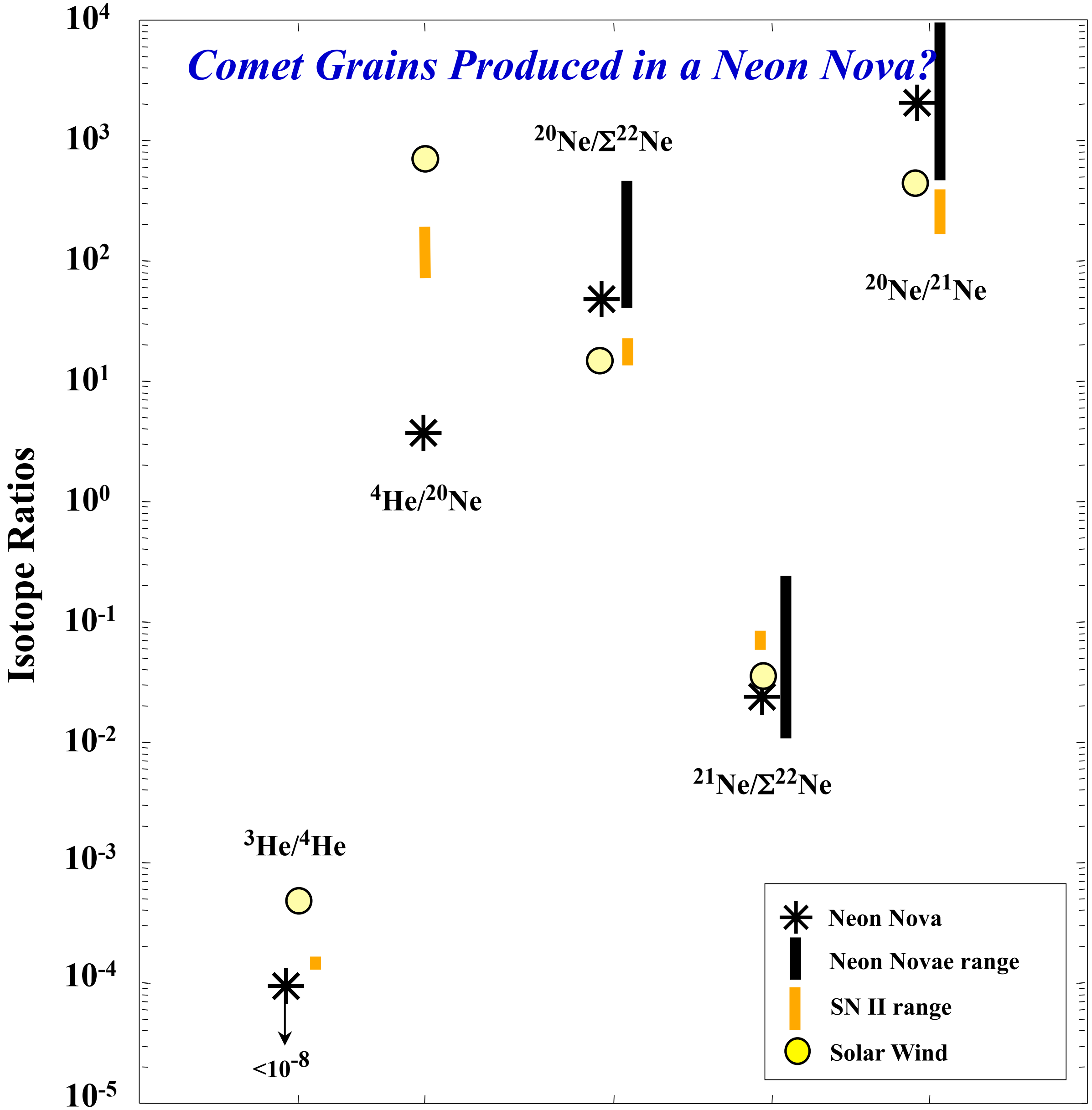

***UIR emission features in the near-IR and thermal-IR are required to fit the IR spectrum***

***From A. Evans et al. 2005, 360, 1483***

# *Comet Grains Produced in a Neon Nova?*

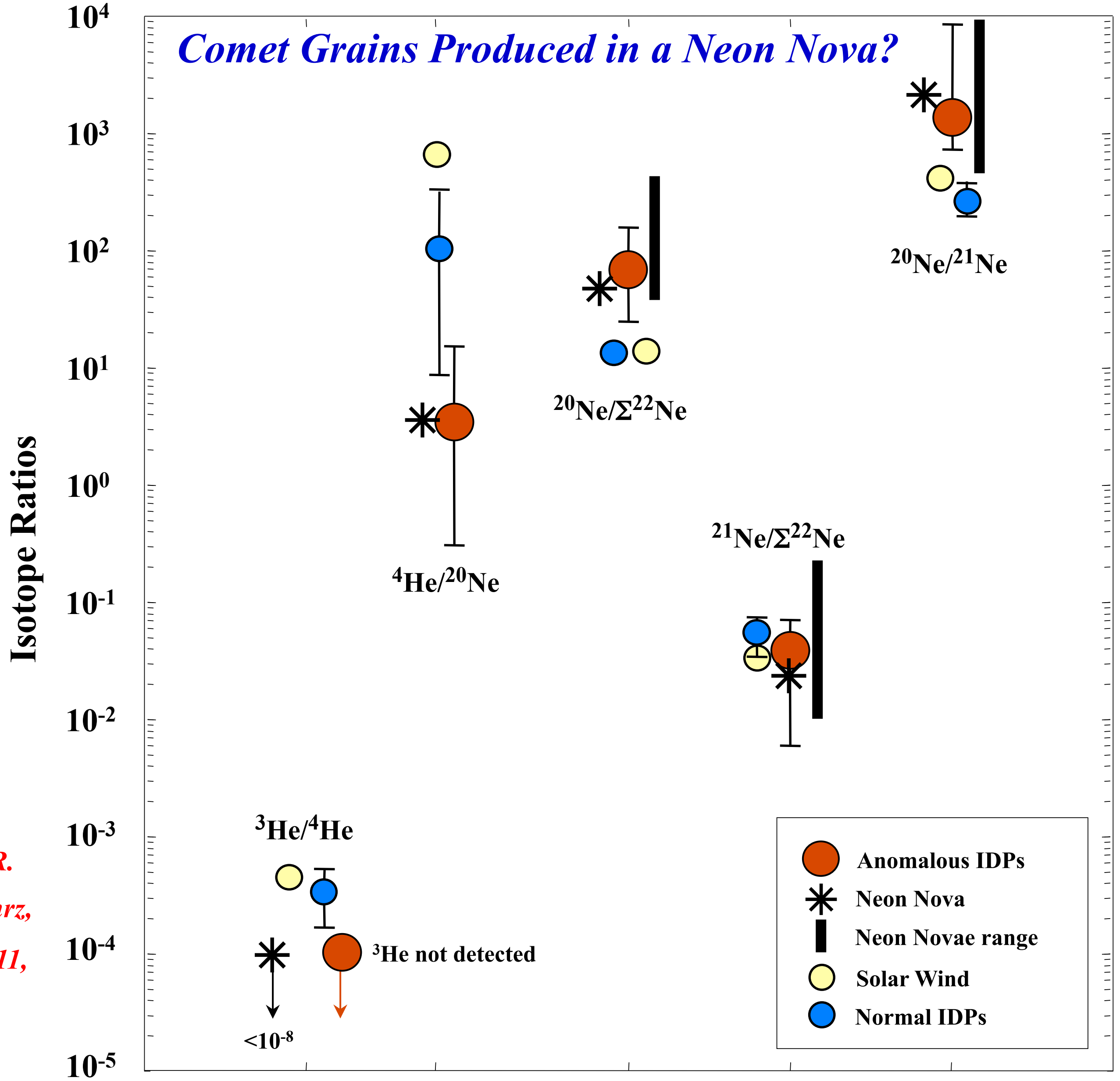



*From R. O. Pepin, R. L. Palma, R. D. Gehrz, and S. Starrfield 2011, ApJ,742, 86*




*From R. O. Pepin, R. L. Palma, R. D. Gehrz, and S. Starrfield 2011, ApJ,742, 86*

## *Comet Grains Produced in a Neon Nova?*




*From R. O. Pepin, R. L. Palma, R. D. Gehrz, and S. Starrfield 2011, ApJ,742, 86*