Infrared Observations of Classical Novae: Outburst Parameters and Abundances in the Ejecta

Chick Woodward

Department of Astronomy, University of Minnesota

Outline

I. *Novae and Galactic Chemical Evolution*

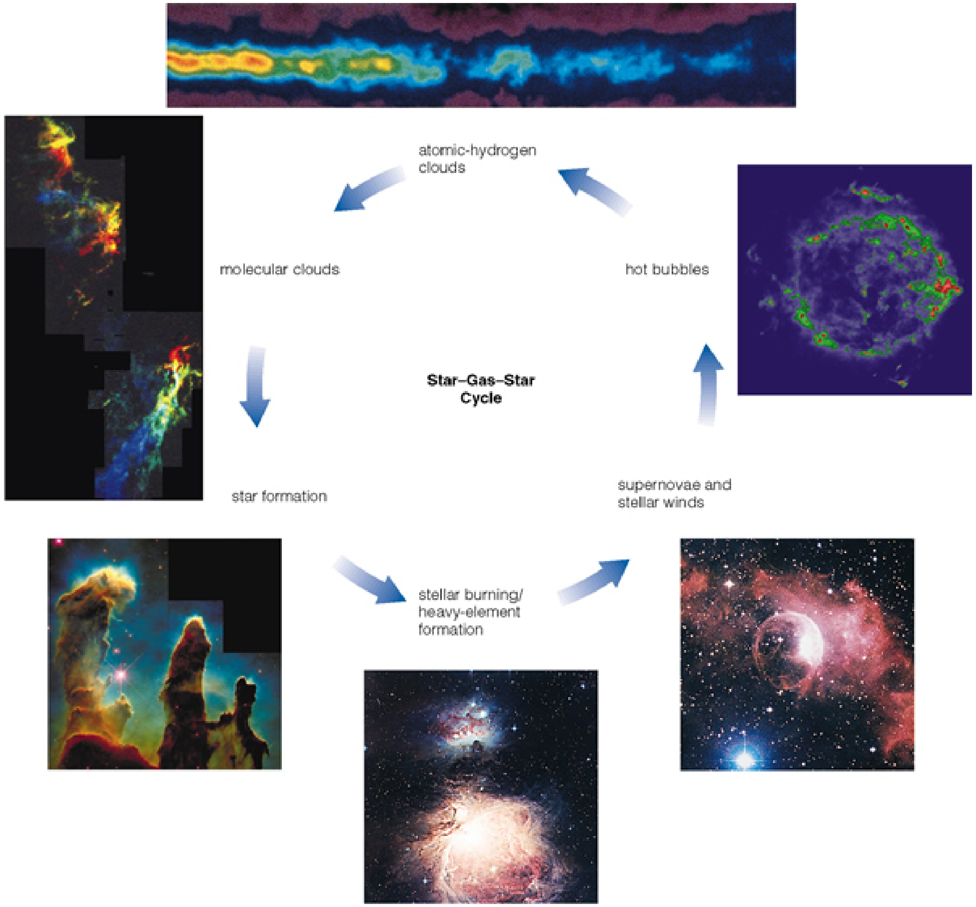
II. *Outburst Parameters from IR Data*

III. *Chemical Abundances in the Ejecta*

IV. *New Spitzer Results*

V. *Concluding Remarks*

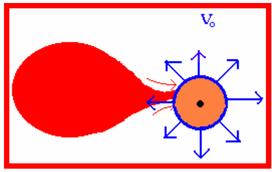
The Role of Novae in Galactic Chemical Evolution



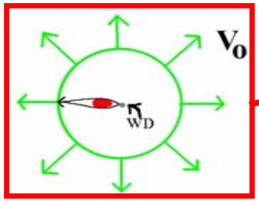
Astrophysical Interest in Novae

- *Along with SNe and Red Giants — Enrich ISM with Heavy Elements*
- *Material Expelled in TNR a Mixture of Partially Burned H and Material Entrained from Surface of the WD*
- *Variations in WD Mass, Luminosity and Composition, and Accretion Rates Produce Ejecta that Display Wide Range of Compositions*
- *In situ Dust Formation Processes Occur as Expelled Material Cools*
- *Spatial Structure and Density Inhomogeneities Useful to Understand the Hydrodynamics and Turbulence of the TNR Event*
- *Two Types — CO (slow speed class) and ONeMg (fast speed class)*

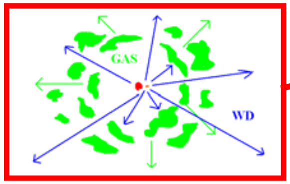
IR Development Phases



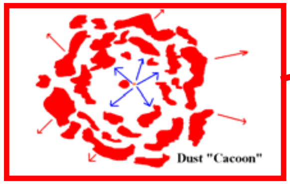
Fireball Expansion Phase



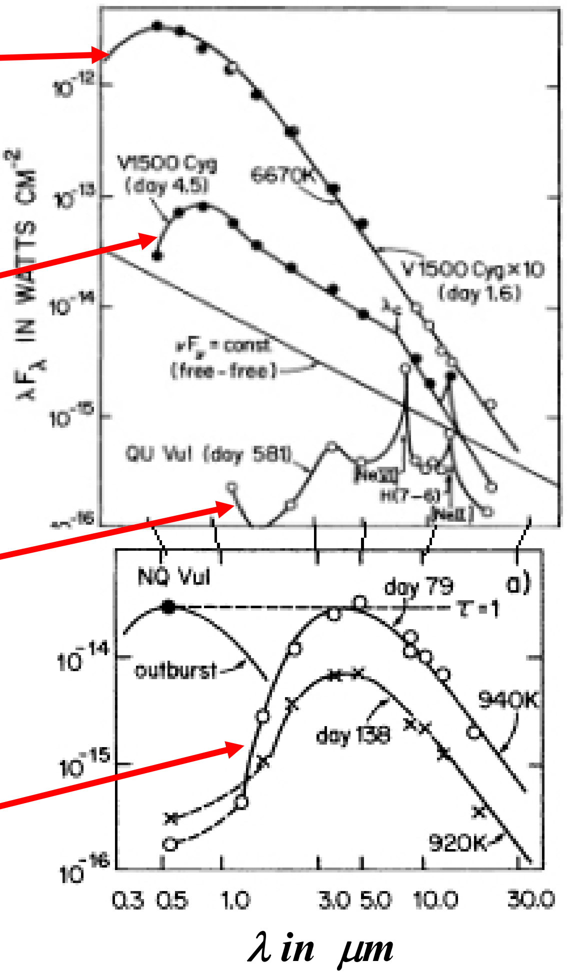
Free-Free Expansion Phase



Coronal Phase in ONeMg Novae



Dust Cocoon Phase in CO Novae

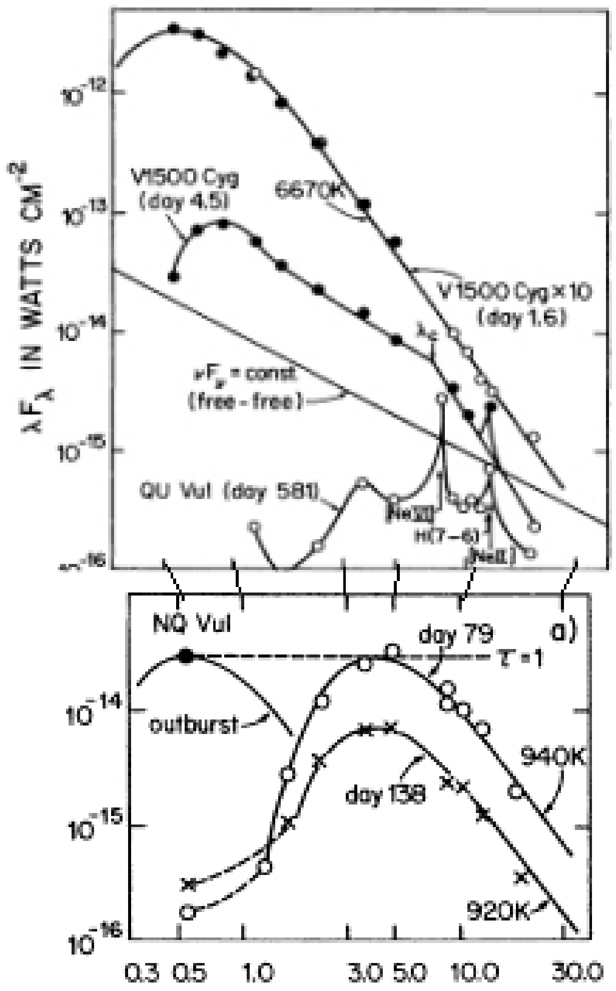


Gehrz et al. 1998, PASP 110, 3

- *The luminosity of the outburst fireball is* $L_o \geq L_{Edd}$
- λ_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 the optically thick dust shell of NQ Vul*

Physical Parameters Derivable from IR SEDs

Gehrz et al. 1998, PASP 110, 3



λ in μm

- ***T_{BB} in K** and time of the outburst **t_o in JD** for expanding photospheres and dust shells*

- ***The apparent luminosity; for blackbodies,***

  $$f = 1.36\ (\lambda f_\lambda)_{max} \text{ in W cm}^{-2}$$

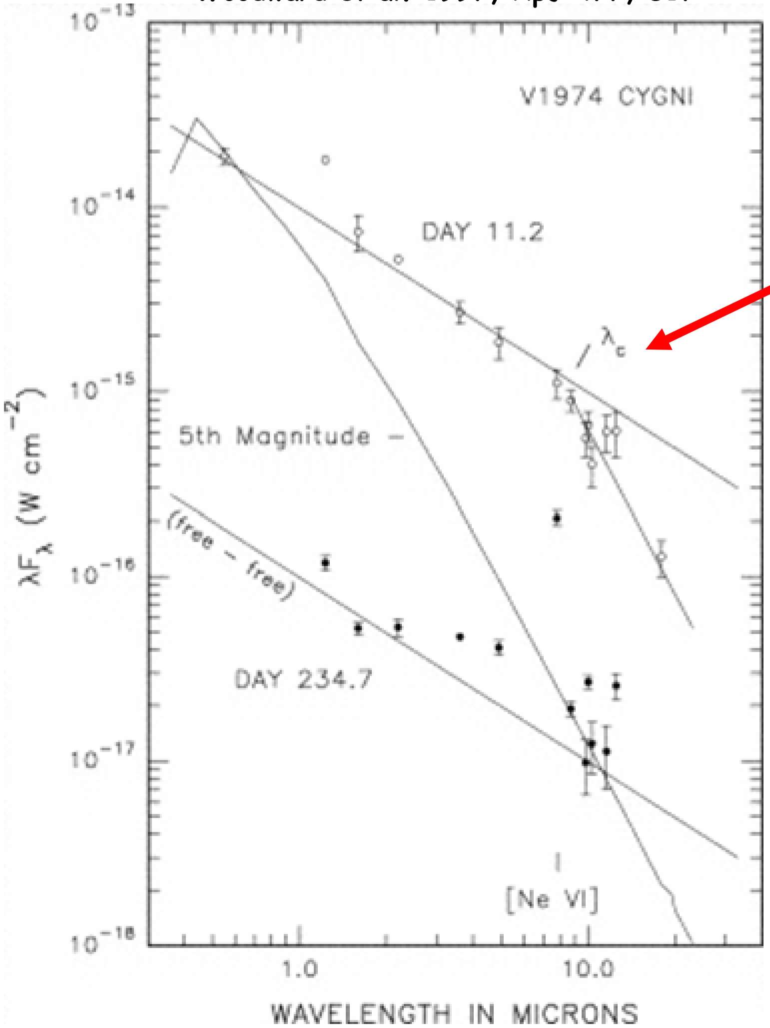
- ***The free-free self-absorption wavelength***

  λ_c in μm

- ***The outflow velocity V_o (km s^{-1}) from emission lines***

Physical Parameters Derivable from IR SEDs

Woodward et al. 1997, ApJ 477, 817



Mass of the Gaseous Ejecta

$$10^{-18}\,\lambda_c^2(\mu m)\; n_e(cm^{-3})\; l(pc) \approx 1$$

Shell Depth

- ***Free-free self-absorption causes the optically thin bremsstrahlung continuum to turn over onto the Rayleigh-Jeans blackbody tail***

Mass of the Ejecta from IR SED's

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

$$M_{gas} \approx 3.3\times10^{-13}\left(V_0 t\right)^2 \quad \textbf{\textit{in}}\ M_\odot$$

- *From λ_c during the optically thin free-free phase:*

$$M_{gas} \approx 5\times10^{-14}\left(V_0 t\right)^{2.5}\lambda_c^{-1} \quad \textbf{\textit{in}}\ M_\odot$$

These two methods give self-consistent results; however, the derived mass are larger that predicted by "theory"

Physical Parameters Derived From IR SEDs

Hayward et al. 1992 (Ap. J., 401, L101)

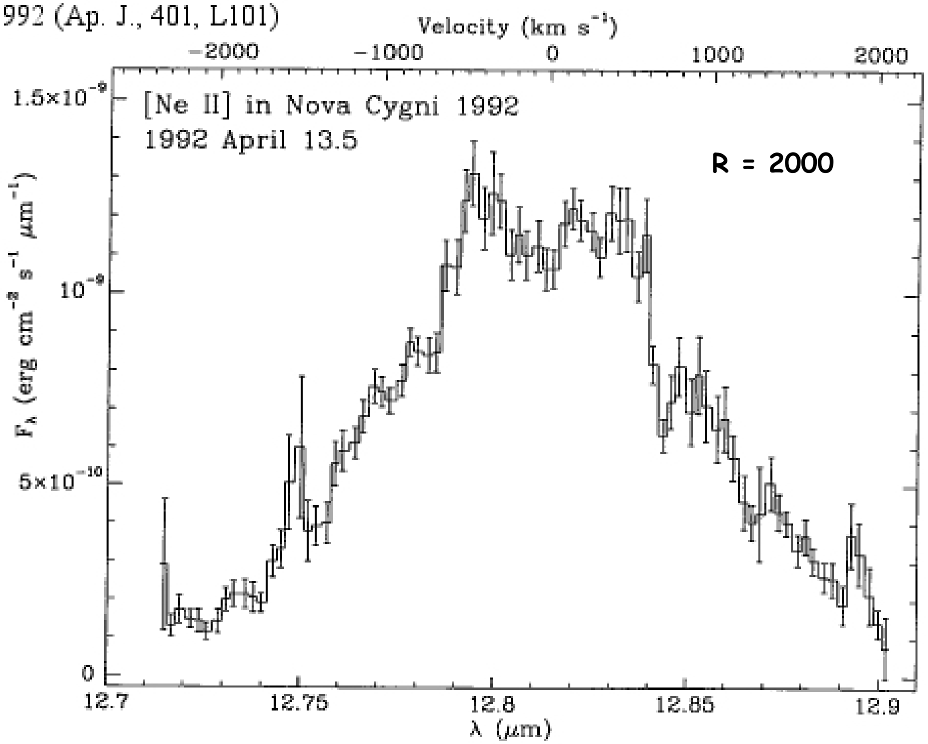
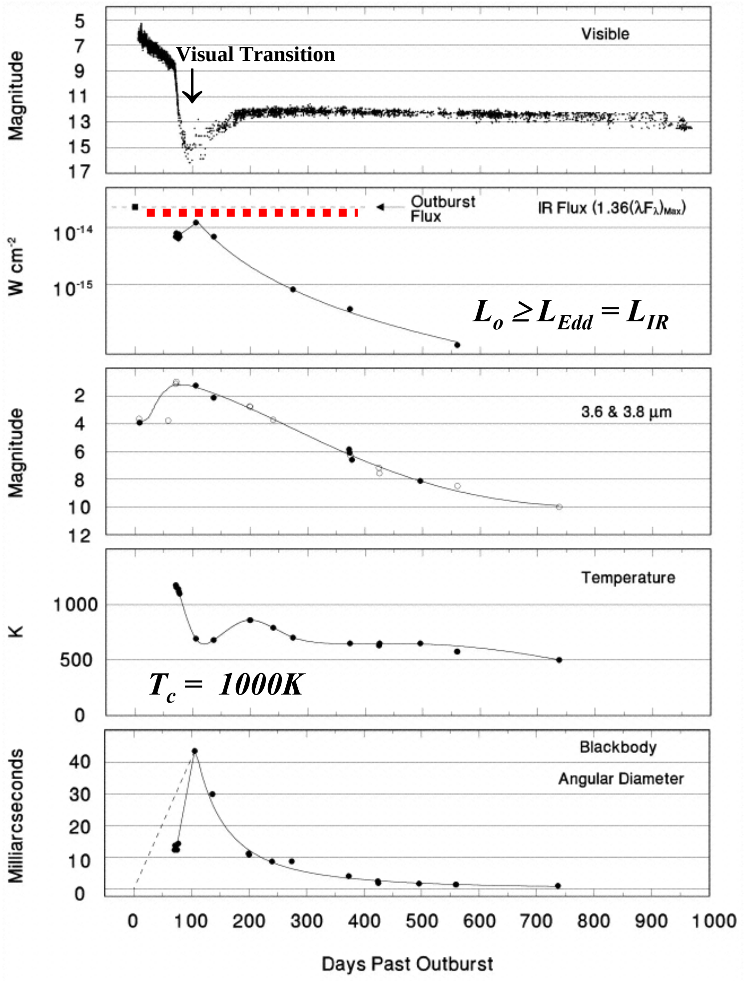


FIG. 3.—High-resolution ($\lambda/\Delta\lambda \approx 2000$) spectrum of the 12.81 μm [Ne II] line. The apparent features at 12.75, 12.87, and 12.89 μm are due to imperfect cancellation of telluric lines.

Profiles give V_o (km s^{-1}) and details give dynamical properties

Dust Condensation in CO Novae

Dust Formation in V705 Cas



Mason et al. 1998, ApJ 494, 783

- $T_c \approx 1000\ K$
- $$R_c = \left[\frac{L_o}{16\pi\sigma T_c^4}\right]^{1/2}$$
- $t_c \approx \frac{R_c}{V_0}$ ***, where V_o is the outflow velocity***

Blackbody Photospheres and Dust Shells: Physical Parameters from IR SEDs

- ***Angular radii:***

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

- ***The distance by expansion parallax:***

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

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

$$L_o \approx 3 \times 10^{17} D^2 f$$ ***in $L_\odot$*** ***Note that $L_o \geq L_{Edd}$***

Dust Mass, Abundances of the Condensables, and Grain Size from IR SEDs

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

$$M_{dust} \approx 1.6 \times 10^{-11} \rho_{grain} V_0^2 t^2 T_{BB}^{-6} \quad \textbf{\textit{in}}\ M_\odot$$

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

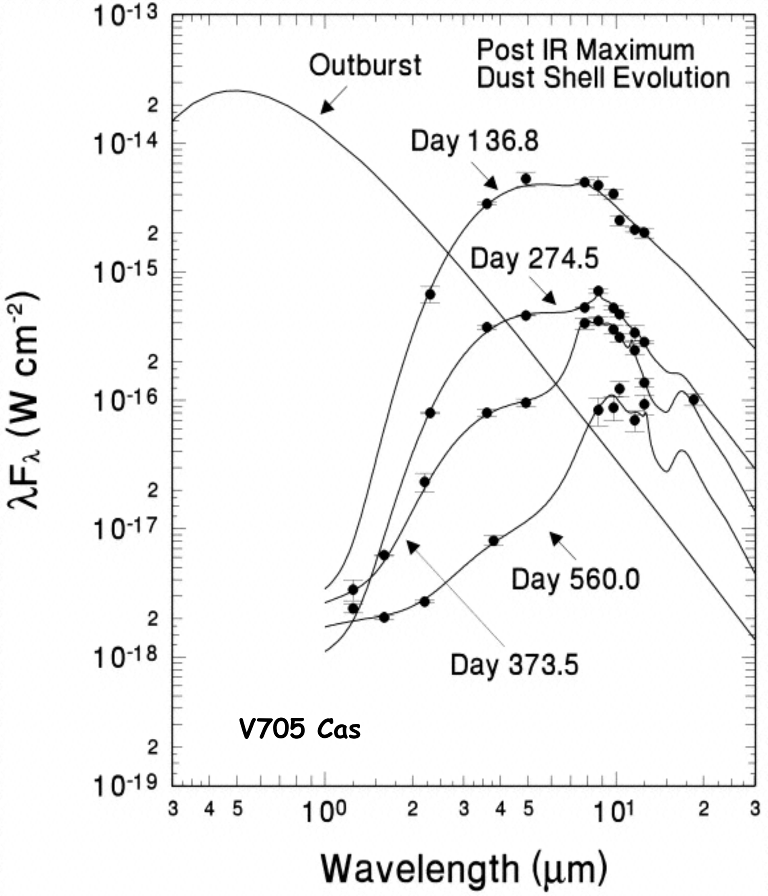
$$\frac{M_{dust}}{M_{gas}} \quad \textbf{\textit{compared to solar abundance}}$$

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

$$a_{gr} \approx 2 \times 10^{22} L_0 V_0^{-2} t^{-2} T_{BB}^{-6} \quad \textbf{\textit{in}}\ \mu m \qquad (a_{gr} \approx 0.2\text{-}0.55 \mu m)$$

Nova Grain Properties

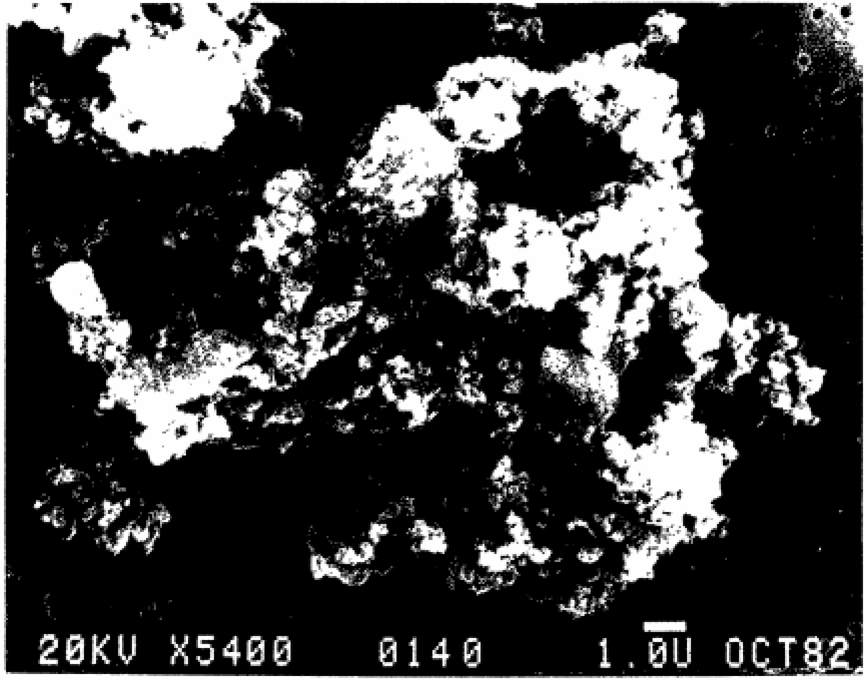
Mason et al. 1998, ApJ 494, 783



- *Novae produce carbon, SiC, silicates, and hydrocarbons*
- *Abundances can be derived from visual opacity and IR emission feature strength*
- *Grain radii are 0.2-0.5 μm*

Interplanetary Dust Particles (IDPs)

Brownlee1985, AREPS, 13, 147



- **Carbon/Silicate composites**
- **CHON component**
- **"Cluster of Grapes" fractal structure**
- **Sub micron grains within a larger fluffy structure (tens of microns across)**

Abundances from IR Spectroscopy of ONeMg Novae

ONeMg Novae result from TNRs on massive ($M \geq 1.2 M_{\odot}$) WDs that result from enhanced He burning in $\approx 10 M_{\odot}$ progenitors.

- ***These TNRs can produce and excavate isotopes of CNO, Ne, Na, Mg, Al, Si, Ca, Ar, and S, etc.***

- ***Several decay reactions can enhance the ^{22}Ne and ^{26}Mg abundances in grains that form in nova outflows. These isotopes are elevated in abundance in meteoritic inclusions (Ne-E and ^{26}Mg anomalies) that may contain pre-solar grains:***

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

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

Abundances from IR Spectroscopy of ONeMg Novae

Often Exhibit IR Emission Lines from Transitions among Fine-Structure Levels of Ground States of Ions of the Heavy Elements

Generally IR Lines Have Very Low Excitation Potentials, $kT_e > 12$ *eV, thus Line Intensities do not Depend on* T_e

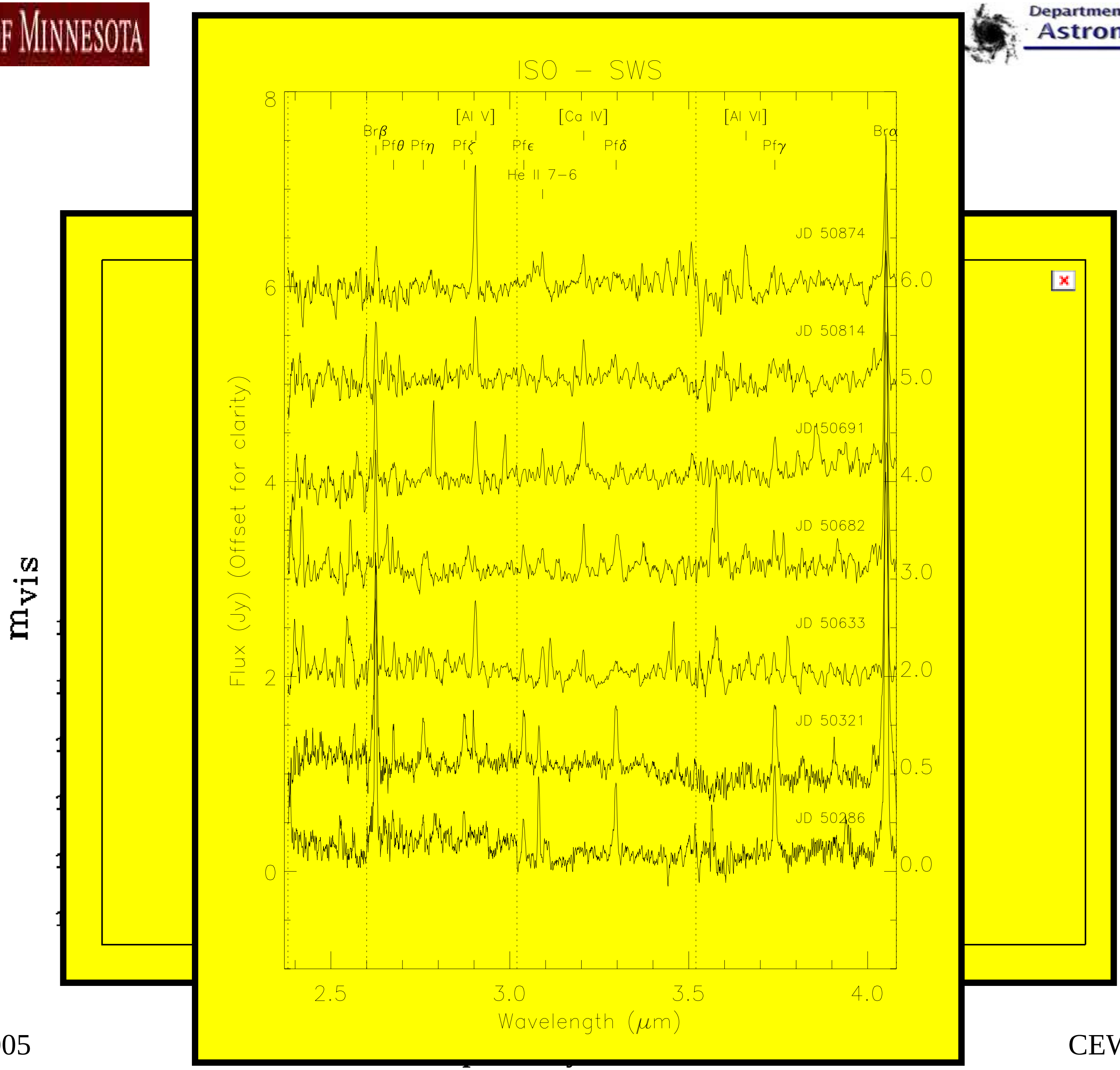
Relative Strengths of IR Lines Yield reliable Ion Abundances (All Collisionally Dominated, Same Dependence on Density)

Typically Lines –

Higher Ionization States [Mg VIII] $\lambda 3.02$ *μm, [Si IX]* $\lambda 3.92$ *μm*

"Coronal Lines"

- *[Ne II]* $\lambda 12.8$ *μm*
- *Arise in the Expanding Ejecta (Speckle Inteferometry Measurements and Velocity Widths of Lines)*


m_{vis}
ISO — SWS
[Al V]
[Ca IV]
[Al VI]
Brβ
Pfθ
Pfη
Pfζ
Pfε
Pfδ
Pfγ
Brα
He II 7–6
JD 50874
JD 50814
JD 50691
JD 50682
JD 50633
JD 50321
JD 50286
8
6
4
2
0
6.0
5.0
4.0
3.0
2.0
0.5
0.0
Flux (Jy) (Offset for clarity)
2.5
3.0
3.5
4.0
Wavelength (μm)

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***
- $(dM/dt)_{novae} \approx 7x10^{-3}\ M_{\odot}\ yr^{-1}$
- $(dM/dt)_{supernovae} \approx 6x10^{-2}\ M_{\odot}\ yr^{-1}$

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

Abundances in the Ejecta of Classical Novae from IR Data

Nova	*X*	*Y*	$\frac{(n_X/n_Y)_{nova}}{(n_X/n_Y)_\odot}$	*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	*Carbon dust*	*H*	≈ 45	*Mason et al. 1997*
V705 Cas	*Ca*	*H*	20	*Salama et al. 1997 (ISO)*
V705 Cas	*O*	*H*	≥ 25	*Salama et al. 1997 (ISO)*
V705 Cas	*Carbon dust*	*H*	≈ 20	*Mason et al. 1998*
V1425 Aql	*N*	*He*	≈ 100	*Lyke et al. 2002 (ISO)*

Contributions of Classical Novae to Abundance Anomalies

CONCLUSIONS

- ***Limits are less stringent on local scales, where a nova is adjacent to or embedded in a molecular cloud potentially lead to significant abundance enhancements of proto-nebular material***
- ***Caveat: Some novae may eject as much as 3-10 times more mass than is predicted by present models because much mass may be hidden as undetected neutral gas (Ferland, 1998).***

Spitzer Science

Mature CNe — First ≈ 2 yrs after Outburst

- $T_{effective}$ *Remnant Rises, yet at some point 'eruption' turns-off*
- *Systems Become Increasingly Faint*
- *Consequent Physical Evolution least Studied in IR*

Aged CNe — ≈ Few Decades after Outburst

- *Mass Transfer From Cool Secondary to WD Restablished*
- *Persistence of Fine-Structure Lines in Ejecta (O, Ne, S, Ca, Si)*
- *Fate and Evolution of Dust Formed in Dusty Events*

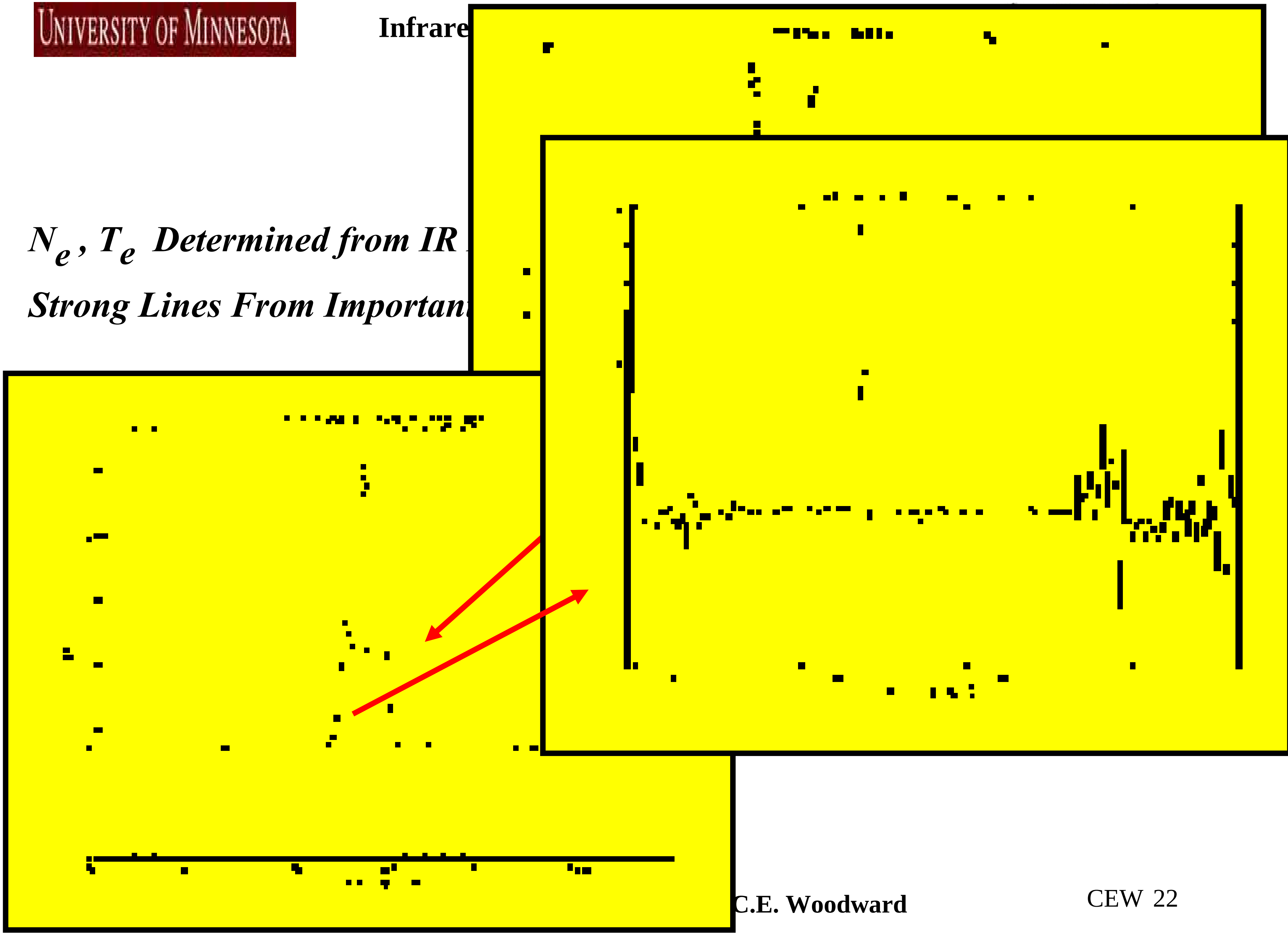
Key Goal —

Determine N_e, T_e, *Relative Metal Abundance, and Dust Composition in Ejecta Late in Evolution*

Infrare

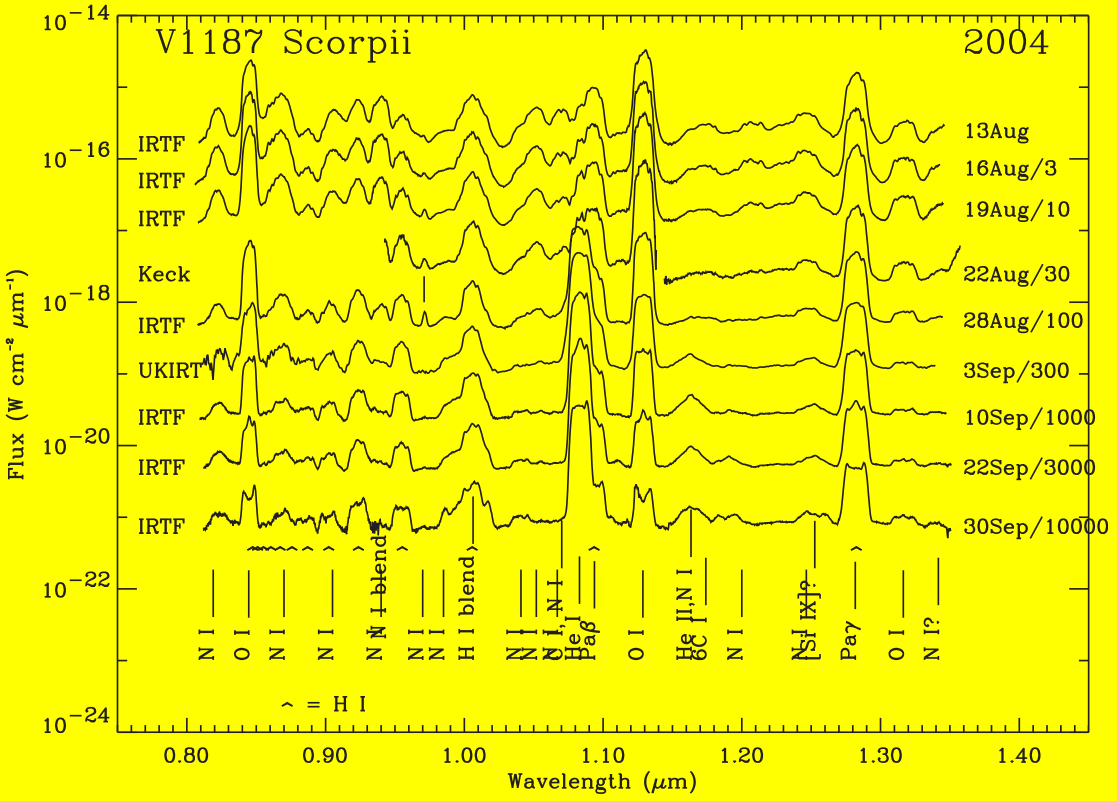
N_e, T_e Determined from IR

Strong Lines From Importan

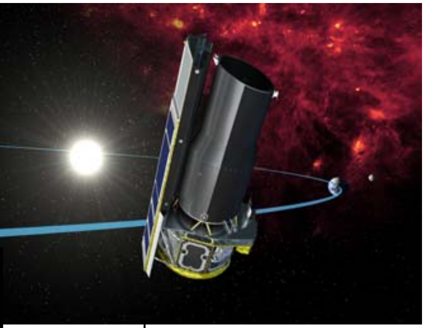


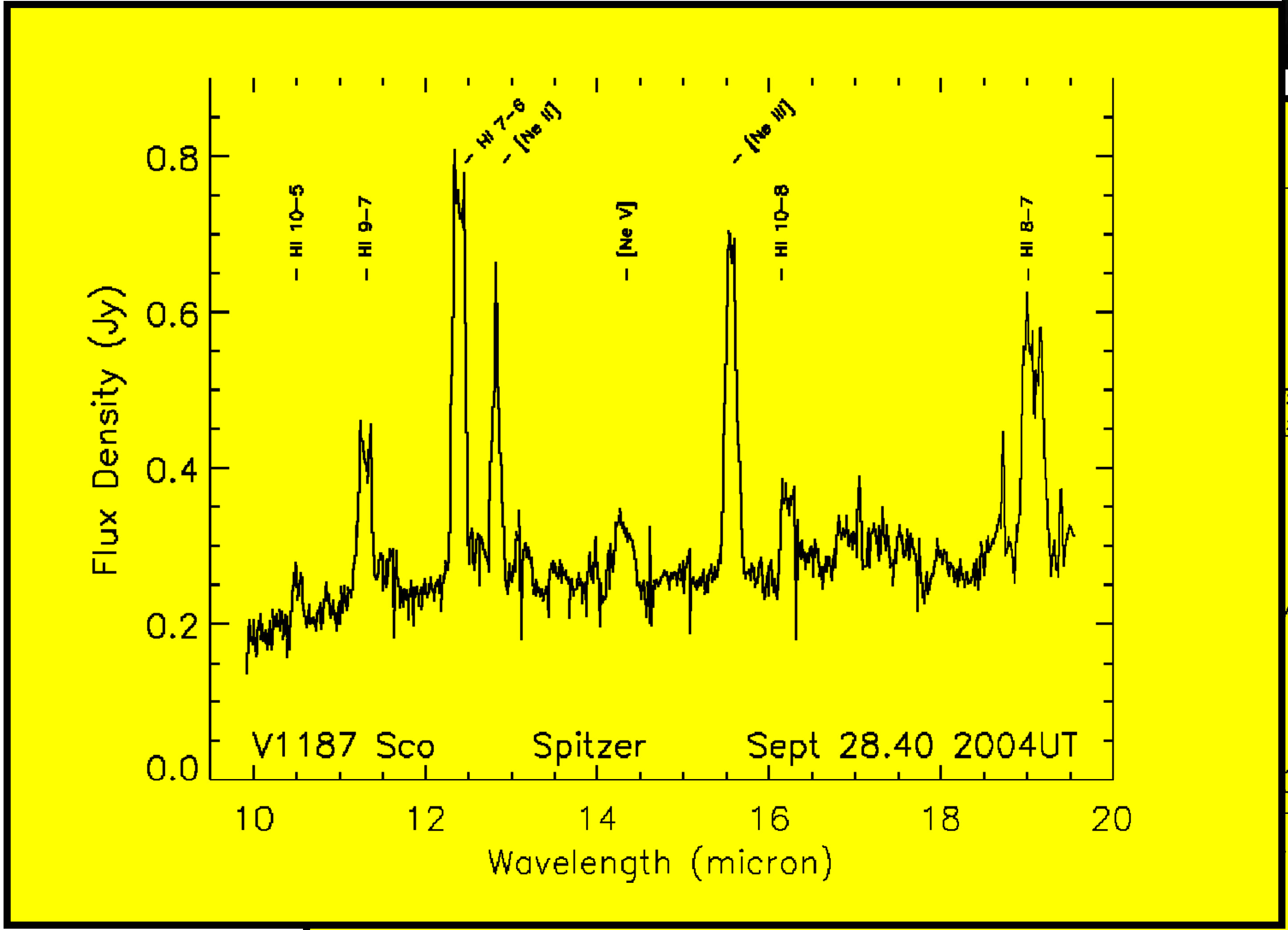
n

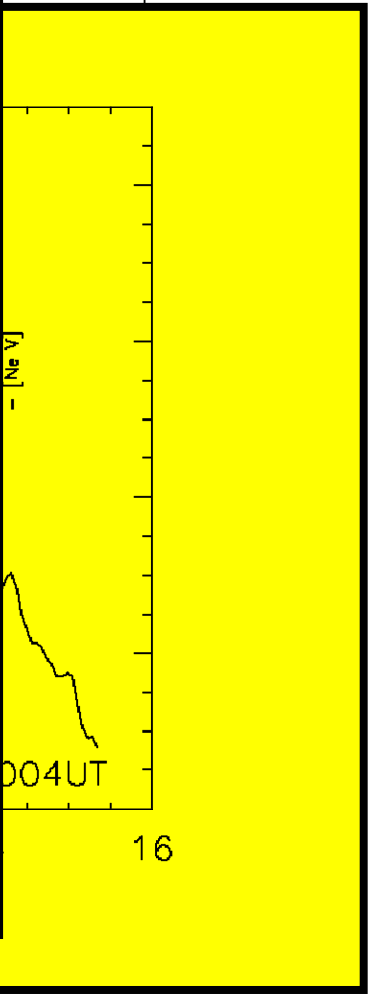
2)


V1187 Scorpii
2004
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
Flux (W cm^{-2} μm^{-1})
IRTF
IRTF
IRTF
Keck
IRTF
UKIRT
IRTF
IRTF
IRTF
13Aug
16Aug/3
19Aug/10
22Aug/30
28Aug/100
3Sep/300
10Sep/1000
22Sep/3000
30Sep/10000
N I
O I
N I
N I
N I
N I blend
N I
N I
H I blend
N I
N I
C I, N I
He I
Paβ
O I
He II, N I
C I
N I
N I
[Si IX]?
Paγ
O I
N I?
^ = H I
0.80
0.90
1.00
1.10
1.20
1.30
1.40
Wavelength (μm)

Temporal Evolution

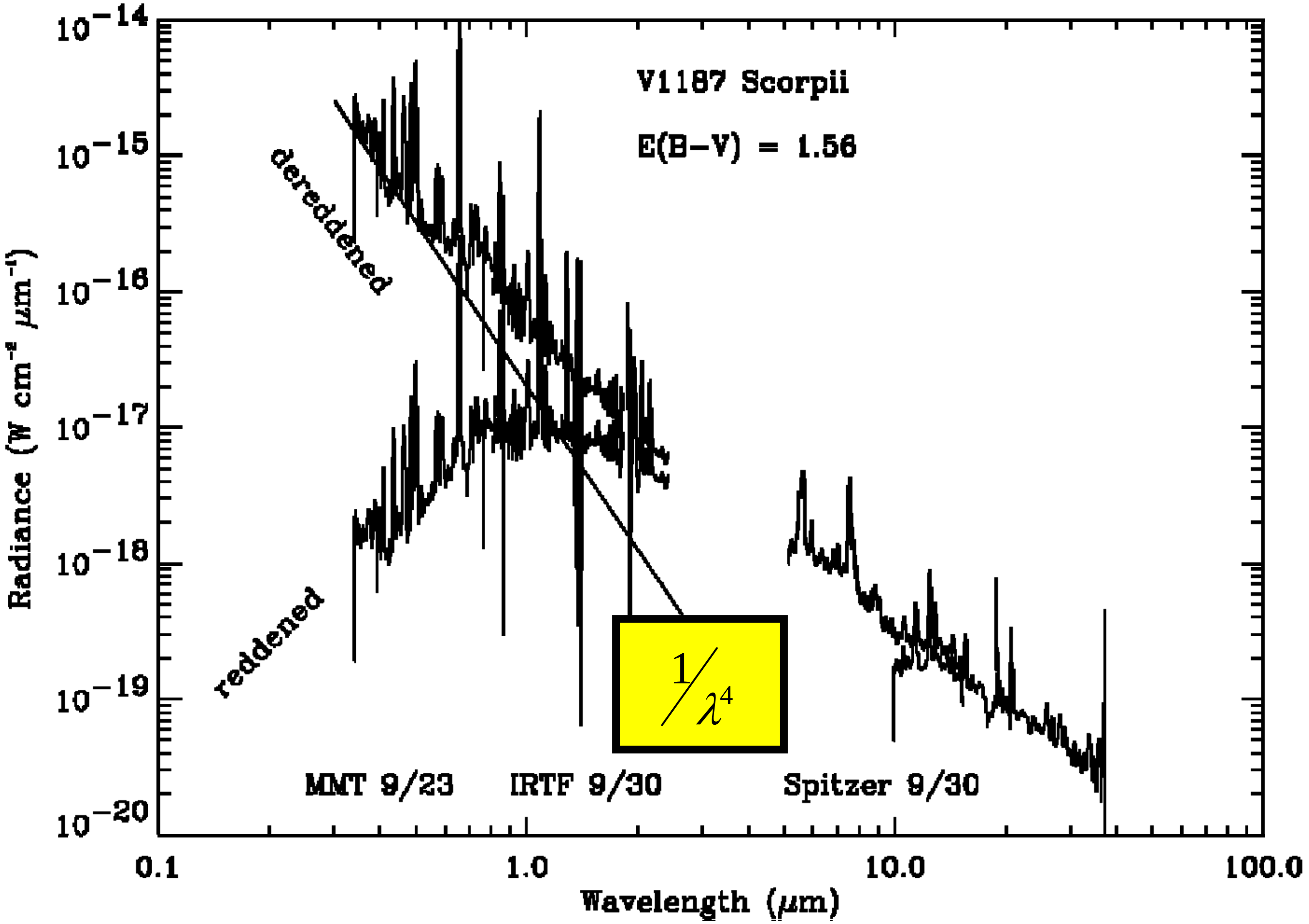






V1187 Sco

Lynch, Woodward, et al. 2005, ApJ (submitted)



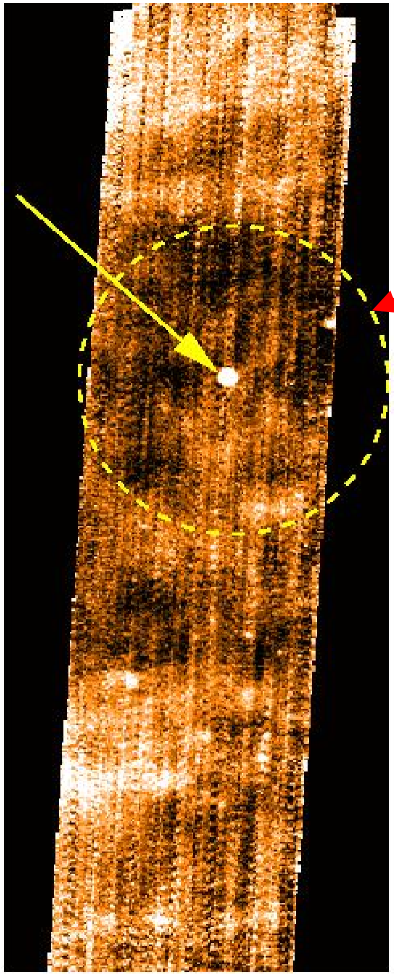
Spitzer ToO — V1187 Sco

Lynch, Woodward, et al. 2005, ApJ (submitted)

Speed Class	Very Fast
t_2	< 8.7 days
t_3	< 15.0 days
White Dwarf	ONeMg
Emission Lines	Complex, Double Profiles
Line Widths	> 4500 km s^{-1}
Reddening E(B-V)	1.56 +/- 0.08
Distance	5.3 +/- 0.6 kpc
Dust Formation	None (May 2005)
Discovery Date	2004 Aug 3.583 UT

Spitzer – Sakurai's Object

Evans, Woodward, et al. 2005 (in preparation)



"HOLE" AND DUST RING

MIPS 70 MICRON SCAN MAP

Summary and Conclusions

- *IR measurements yield quantitative estimates for physical parameters that characterize the nova outburst:* D, L_o, M_{gas}, T_{dust}, a_{dust}, M_{dust}, V_o, L_o, *and abundances*
- *There are large overabundances (by factors of 10-100) of certain metals in the ejecta of CO and ONeMg novae: CNO, Ne, Mg, Al, S, Si*
- *Novae may therefore affect ISM composition on local, and possibly global, scales in the Galaxy*

Summary and Conclusions

- ***The mineral composition and size distribution of the "stardust" made by some CO novae are similar to those of the small grains released by comets in the Solar System***
- ***Theory shows that nova TNRs can produce ^{22}Ne (Ne-E) and ^{26}Mg***
- ***Novae are therefore a potential source for at least some of the solids that were present in the primitive Solar Nebula***

Future Research

- ***Physical parameters and abundances for a larger sample of novae to improve statistics***
- ***Observations of Dusty Novae with Spitzer to Investigate Grain Properties***
- ***Observations of Extremely Old Novae to Determine System Evolution Toward Quiescence***
- ***Synoptic Study of the Variable Population in M33 with Spizer***

IR Observations of Classical Novae: Collaborators

- *University of Minnesota: R. D. Gehrz, T. J. Jones*
- *Keck Observatory: J.E. Lyke*
- *Gemini Observatory: T.R. Geballe, T.L. Hayward*

UK and Europe: M. Barlow, A. Evans, J. Krautter, A. Salama, S.N. Shore

- *Others: M. Greenhouse (GSFC), S. G. Starrfield (ASU), J. Truran (U. Chicago), R. E. Williams (STScI), D. H. Wooden (NASA ARC), G. Schwarz (U. Arizona), K. Vanlandingham (Columbia U.), R. Rudy (Aerospace Corp.), D. Lynch (Aerospace Corp), R. Russell (Aerospace Corp.), M. Klapisch (NRL)*

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