NIR and MIR data on SNe Ia
or
Low Carbon Abundance in Type Ia Supernovae and Other Interesting Clues to the Explosion

J. Craig Wheeler
KITP Accretion and Explosion: Astrophysics of Degenerate Stars

Collaborators

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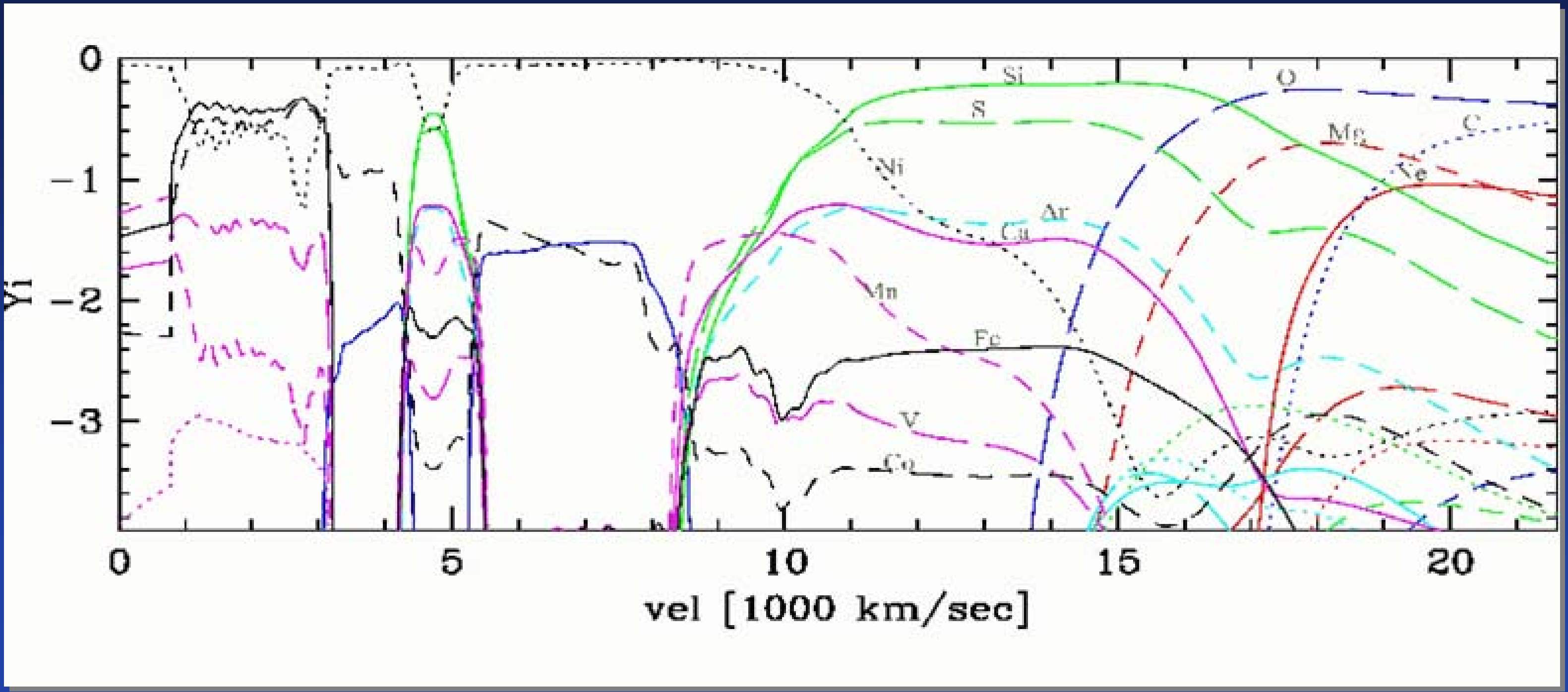
Nomoto, Motohara - Subaru team
The Mid-Infrared Supernova Consortium (MISC) team - Meikle et al.

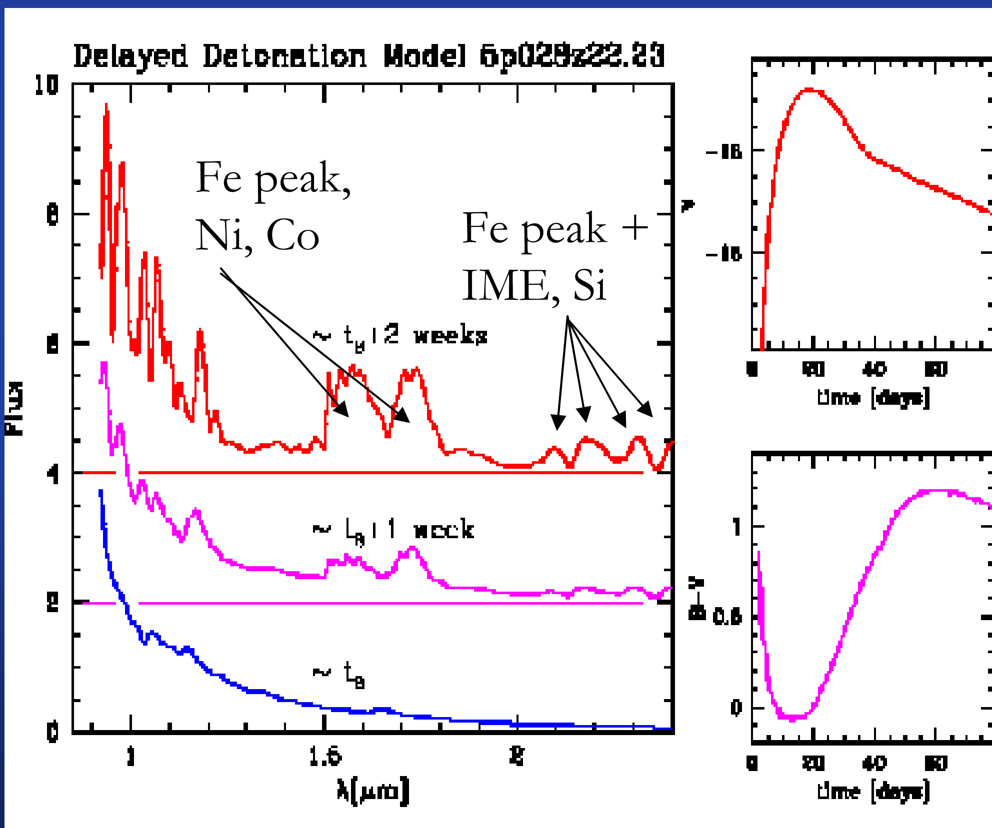


Spherical Delayed Detonation Models - Höflich

- Region of complete burning to NSE
  - 0 to ~ 9,000 km s^{-1} ($T > 5.5 \times 10^9$ K)
- Explosive O burning and incomplete Si burning
  - 10,000 – 15,000 km s^{-1} ($5 \times 10^9 > T > 3 \times 10^9$ K)
- Explosive C burning produces: O, Mg, Ne
  - velocities > 14,000 km s^{-1} ($T < 3 \times 10^9$ K)

Model Predictions: NLTE spectra and light curves

Höflich (From Wheeler et al. 1998)



- M_V = -19.21 at +18.5 d
- M_B = -19.31 at +17.5 d
- Mg II lines (0.922 and 1.091 μm) requires abundance > 1-2%
- After M_V features from Fe groups dominate spectra (1.5 and 1.8 μm)

The Search for Unburned Material

The near infrared (0.8-2.5 μm) has several OI and CI lines.

“Snapshot” program

36 NIR spectra obtained before V_{max} at the IRTF using the SpeX instrument.

LRS mode includes the OI line at 0.7774 μm.

Pre and Near Maximum

-13d to +2d

v_{exp} = 10,000--14,000 km s^{-1}

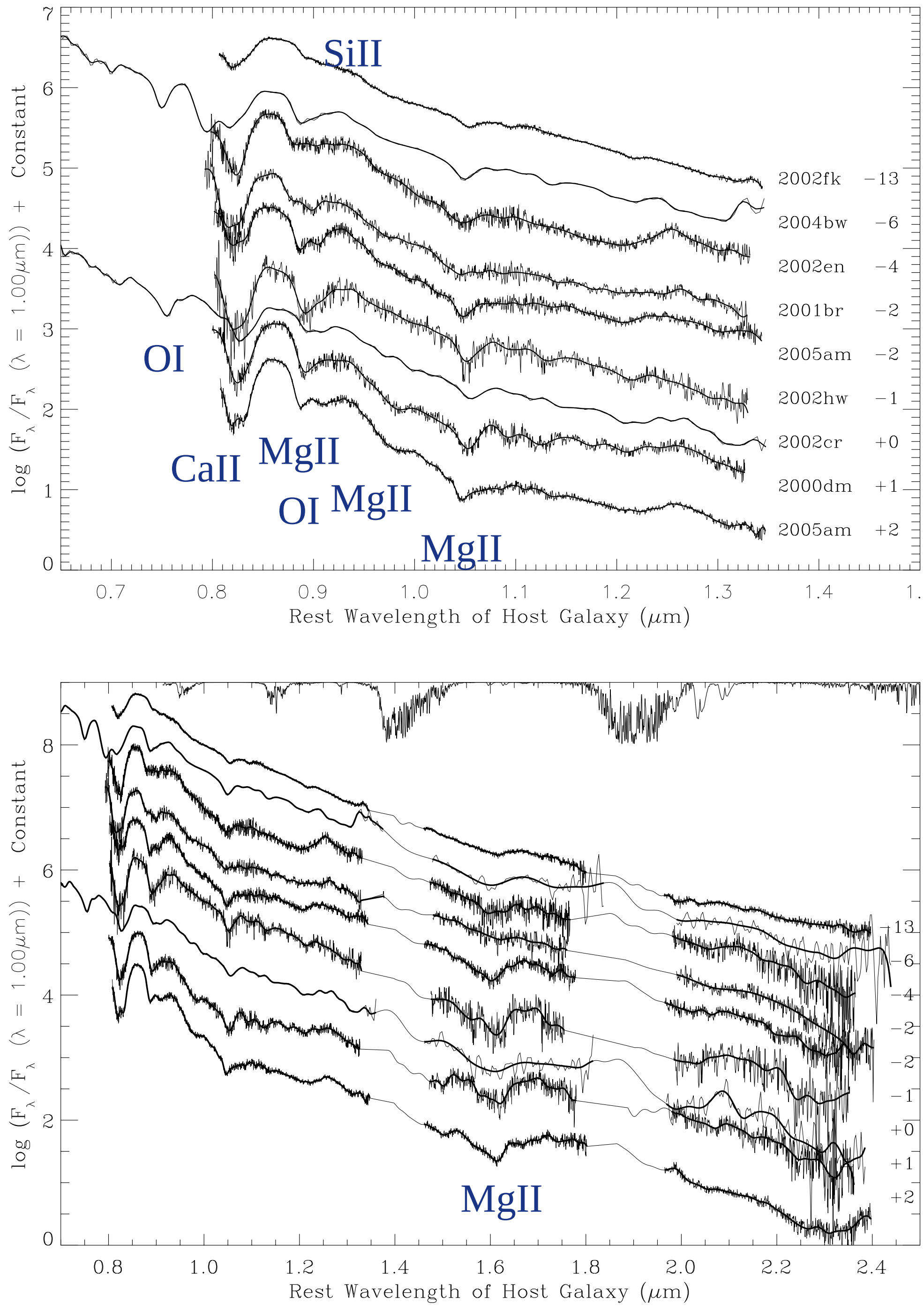
OI – 2 lines

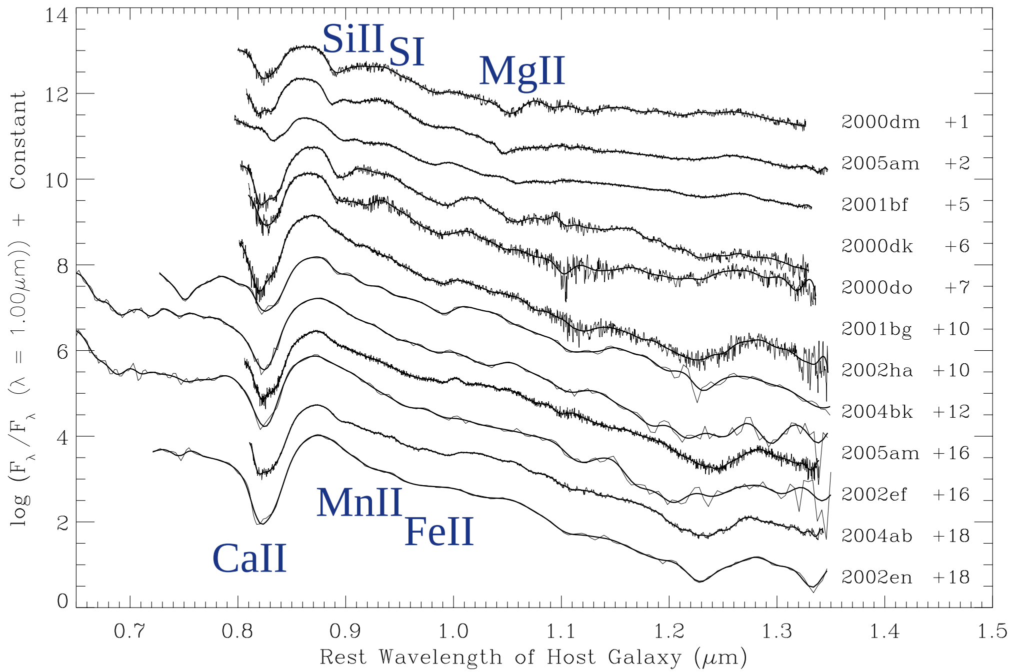
MgII – 4 lines

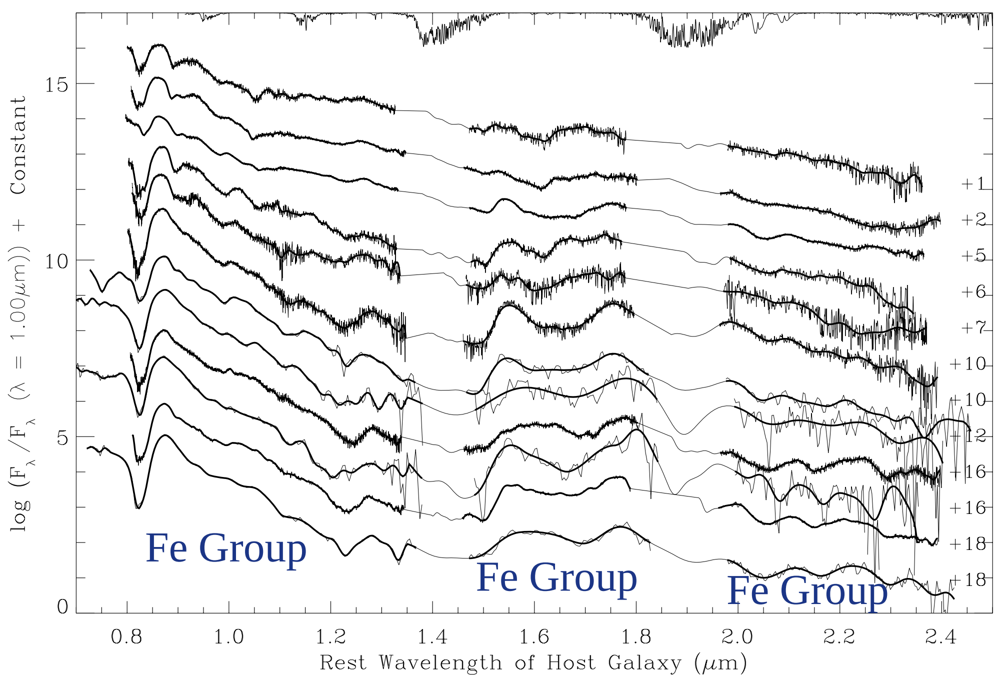
OI & MgII occupy same physical space

No C, no He

We use estimates of line strengths to identify features







Post Maximum

+1d to +18d

v_{exp} = 9,000--12,000 km s^{-1}

MgII fades

FeII has one strong line

Fe group line blanketing

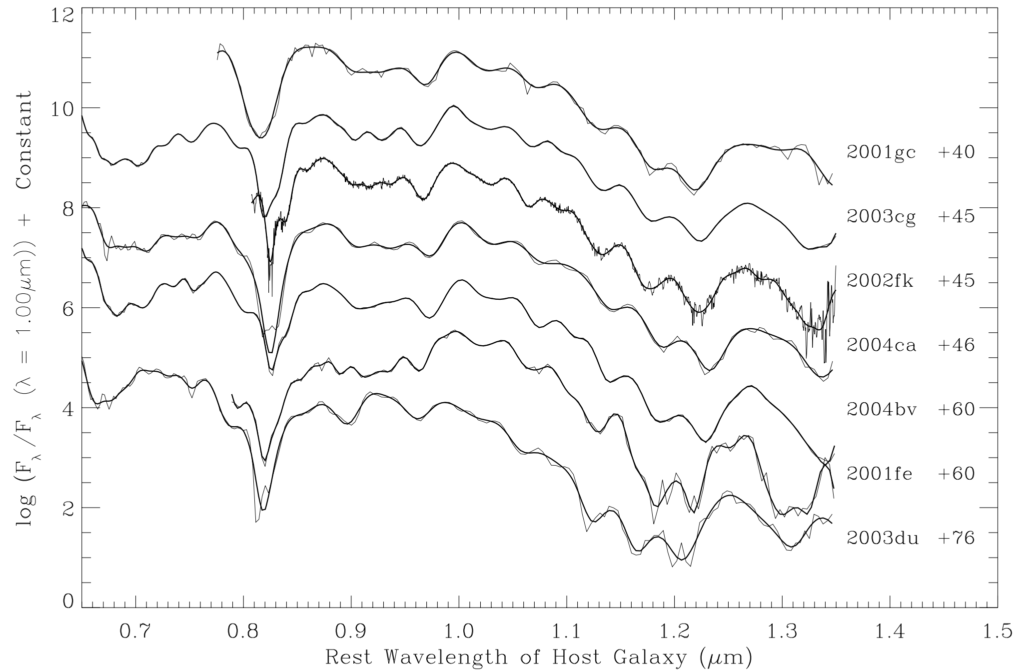
Possible SI

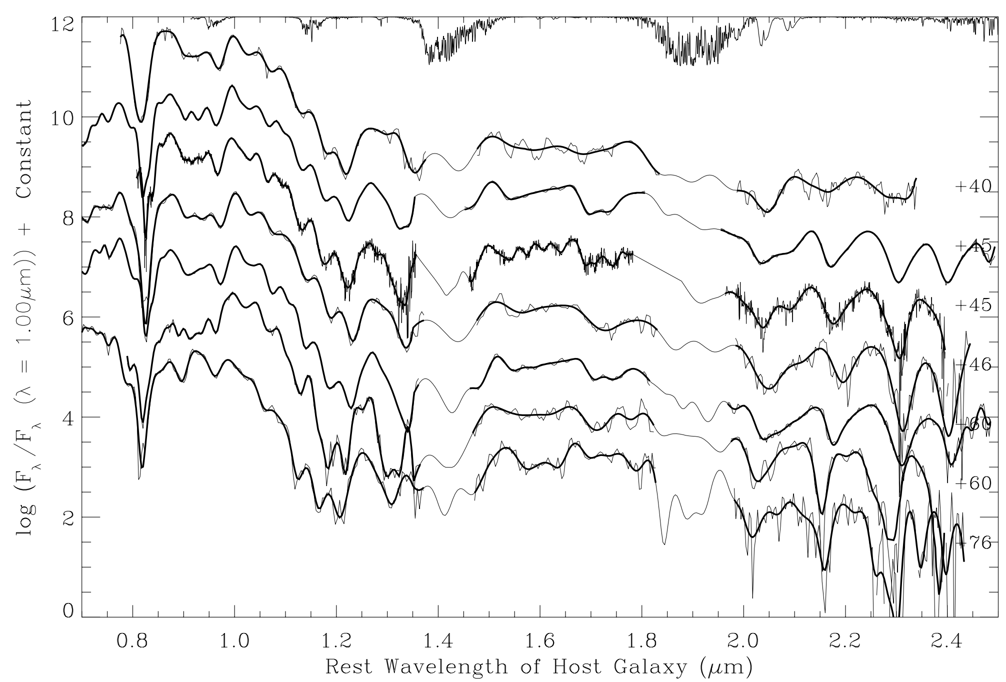
Possible MnII

Transition Phase

+40 to +76d

- No longer a defined photosphere
- Except where line blanketing forms a pseudo-photosphere
- Fe-group emission
- Some CoII resolved

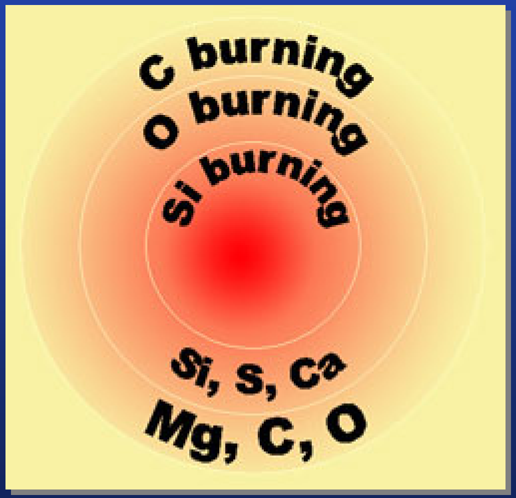


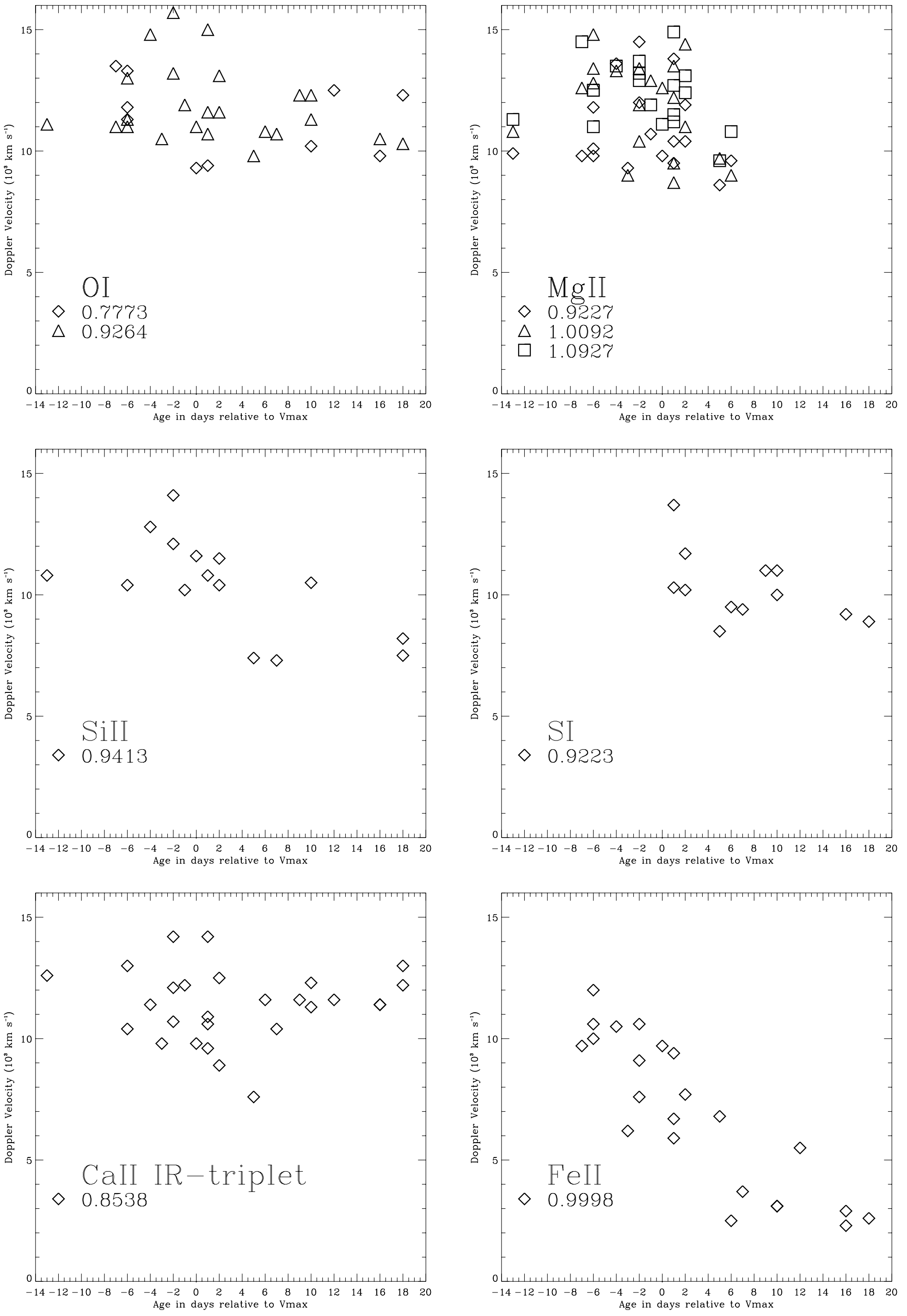


The Results

Distinct minimum velocities shows that burning products are found in distinct layers

Composition of layers is predicted by DD models





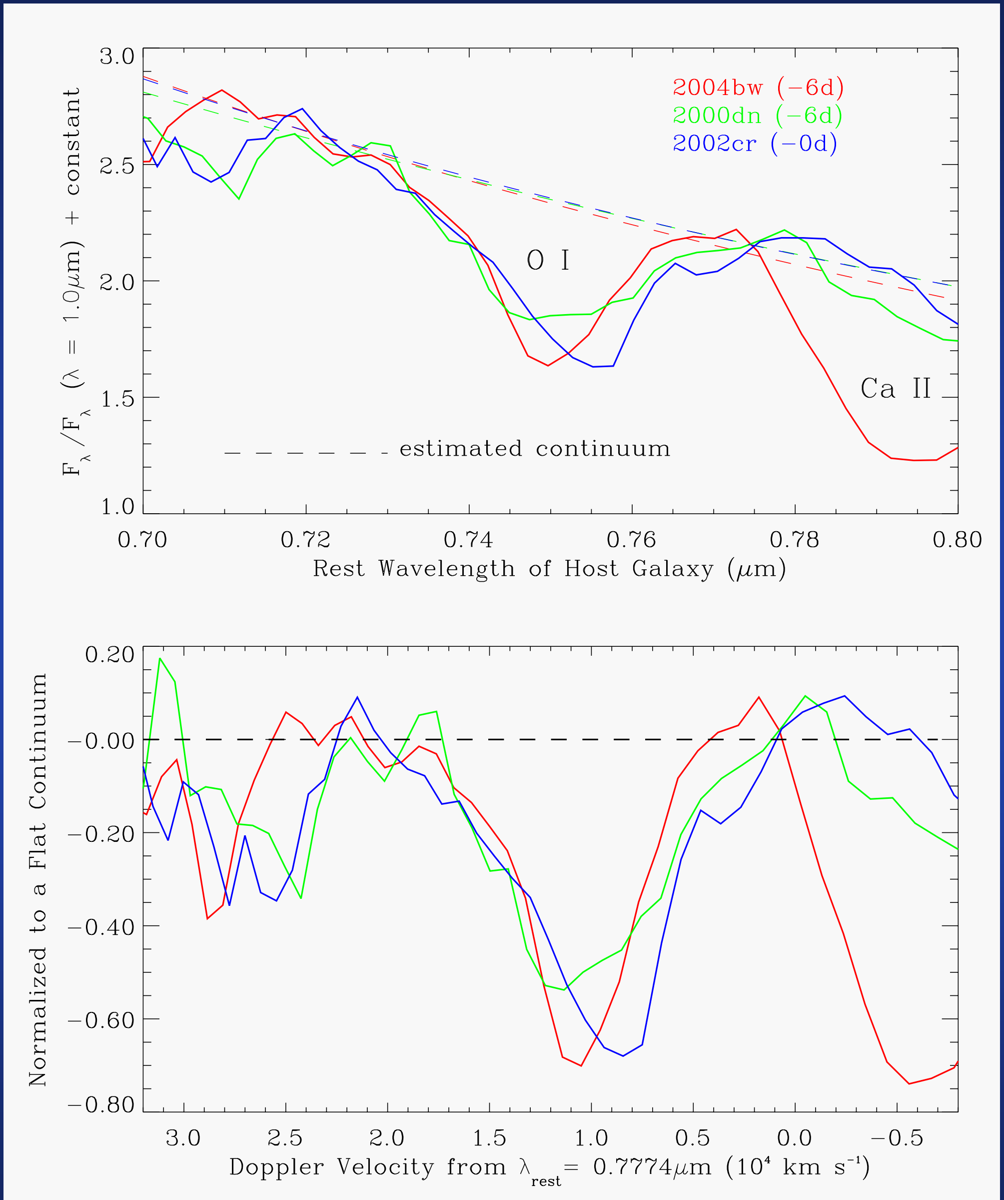
The Composition of Unburned Matter

- **Pristine matter from the progenitor consists of carbon and oxygen in approximately equal abundance**
  - W/D accretes matter through Roche-lobe overflow from a companion
  - Shell burning in low pressure and high temperature produces C and O with mass ratio near unity

The Composition of Unburned Matter

- **C and O in the outer layers have predominantly the same ionization stage**
  - Radiative transitions are rapid in time and space
  - Ionization balance determined by Fe-group photo-ionization boundaries
  - Difference in first ionization potential for C and O $\sim$1-2 x 10^3 km s^{-1}
  - Size of OI region is $\sim$9 x 10^3 km s^{-1}

Velocity Space of OI



OI is detected with Doppler velocities ~ 9-18 x 10^3 km s^{-1}.

If the oxygen features are due to unburned material, then carbon should be present in the same physical space.

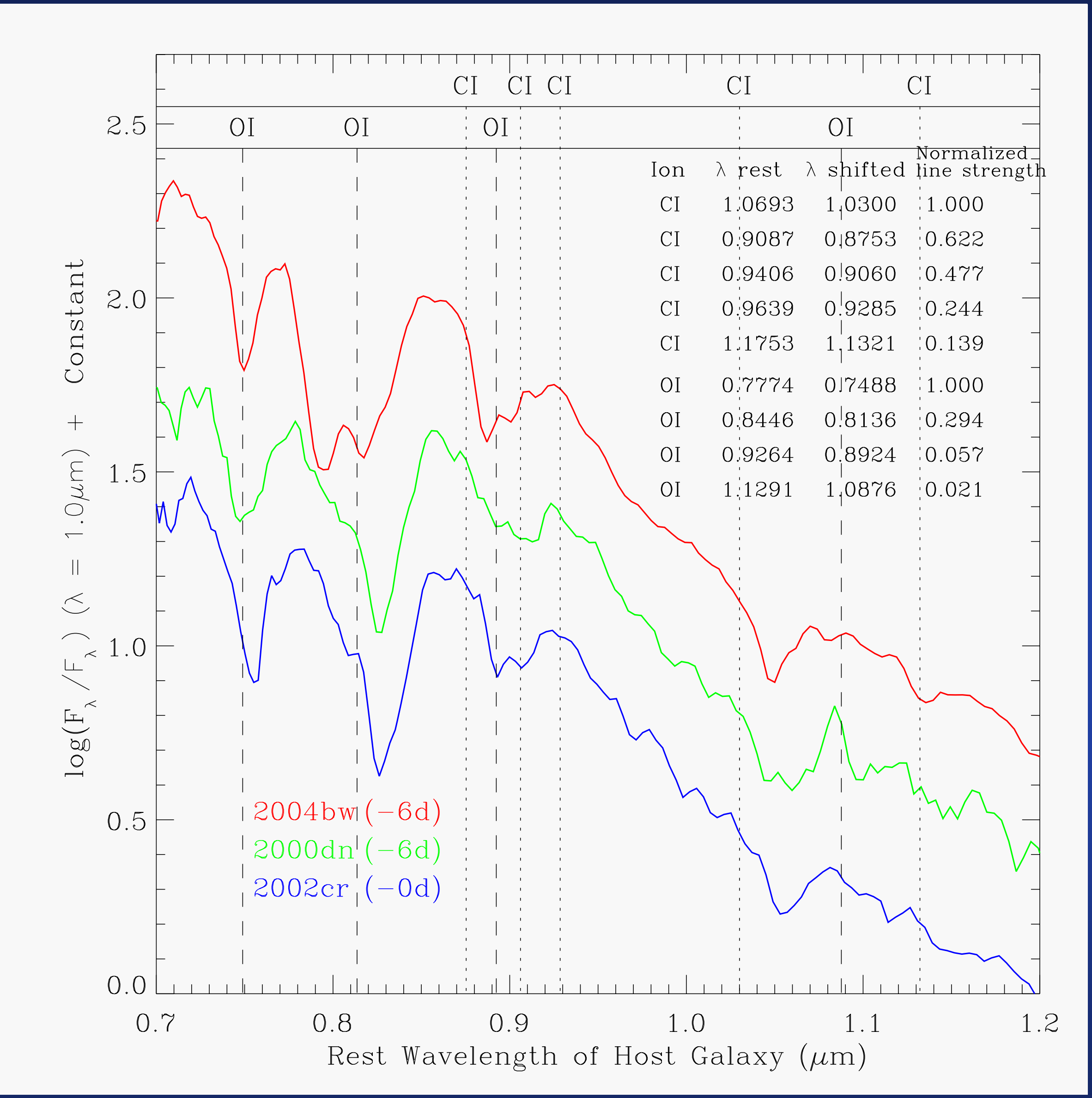
If the oxygen detection is due to explosive carbon burning, then magnesium is expected in the same physical space.

Figure from Marion, et al. 2006

Estimating Relative Line Strengths for O and C (Marion et al. ApJ. 645, 1392, 2006)

The strongest CI line (1.0693 μm) is estimated to be 49.7 times stronger than the strongest OI line (0.7774 μm), given equal abundance and departure from LTE.

Search Results



No evidence for carbon (CI or CII).

The most likely CI feature is at 1.135 μm in the spectrum from SN 2004bw.

A strong detection is made from OI at $\lambda_{rest} = 0.7774\ \mu m$

Figure from Marion, et al. 2006

OI is found between 9 -18 x 10^3 km s^{-1}

Velocity Space for MgII is the same as for OI

The line-forming region for OI comprises about one third of the matter in SNe Ia and extends to the outer layers.

Any matter from these SNe Ia containing C and O in nearly equal abundance, must have an expansion velocity in excess of 18,000 km s^{-1}.

The upper limit on the mass of carbon beyond this velocity is: 3.6 x 10^{-2} solar masses.

Relative Abundance of OI and CI

Oxygen is more abundant than carbon by factors of $10^2 – 10^3$ at ≈ 11,000 km s^{-1}
(confirmed by Tanaka; seminar last Friday)

OI/CI remains well above unity to velocities in excess of 18,000 km s^{-1}

No Carbon in the Extreme Outer Layers

Quimby, et al. (2005) show that SiII is present in optical spectra of SNe Ia to velocities of ≈ 24,000 km s^{-1}.

Silicon in this region can only be produced from a C/O WD progenitor by explosive O burning at temperatures greater than those required to burn C into O and Mg.

All results are consistent with DD Models for Branch “Core Normal” SN Ia

Deflagration to Detonation Transition models for SNe Ia predict observations of:

1. Concentric layers of burning products
2. Lack of carbon in all regions
3. OI and MgII in the same physical space (C burning products together)

DD Models for subluminous SN Ia

Höflich et al. (2002)

Delayed Detonation model for SN 1999by chosen to match optical light curve, small ^{56}Ni mass, ~ 0.1 solar mass

Predict unburned C above ~ 15,000 km s^{-1}

Predict, observe CI line (1.0693 μm)[and O and Mg]

=>

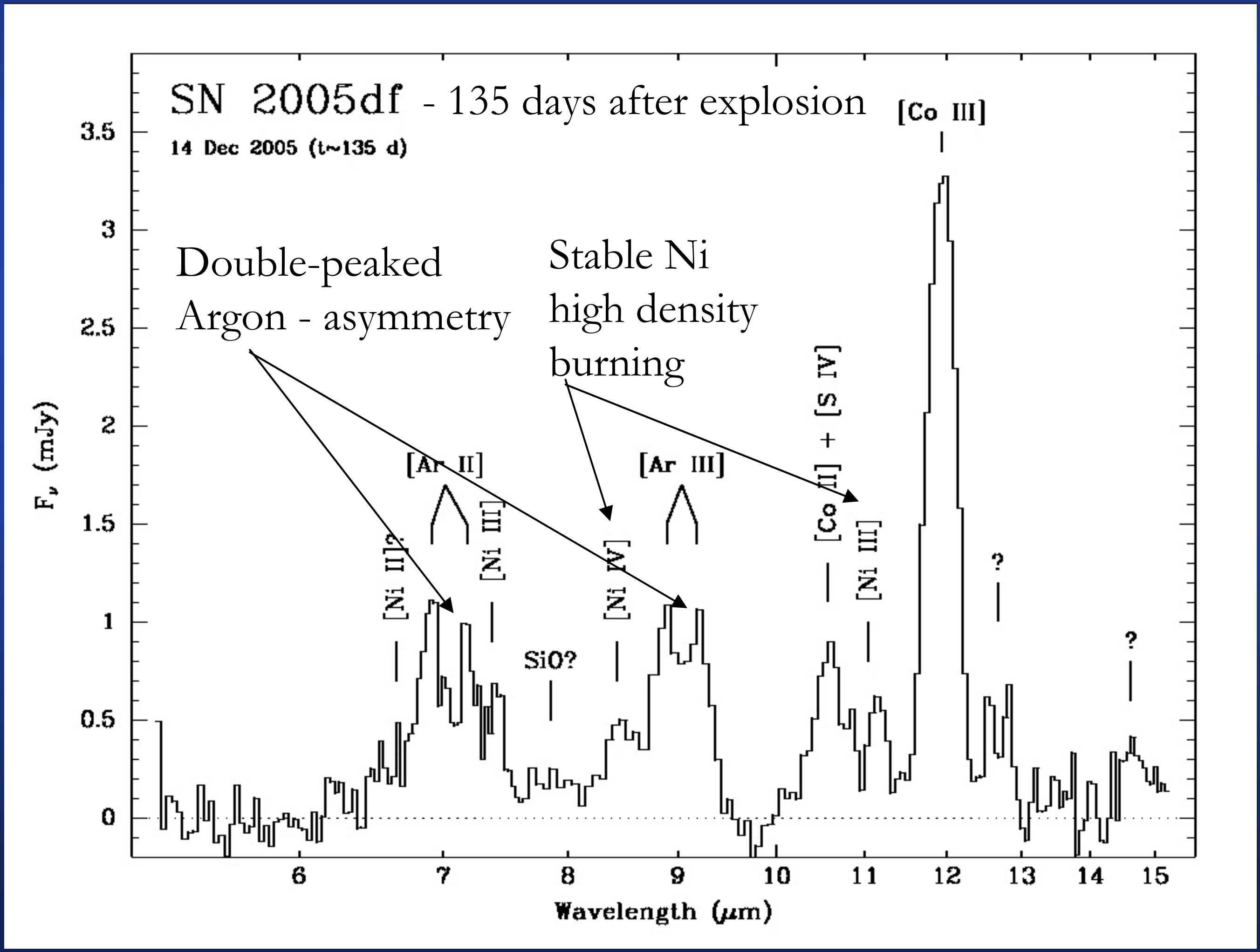
Can observe CI when present

DD models can reproduce optical and NIR aspects of spectral evolution of normal and subluminous SN Ia

First MIR Observations of SN Ia

Gerardy et al. astro-ph/0702117

Layered Ni ⇒ Co ⇒ Ar
Not fully mixed in inner layers
Not pure def, but also not spherical DD?



Stable Ni in center implies “hole” in ^{56}Ni, consistent with flat-top Fe, Motohara et al.

Summary

- Matching peak brightness, light curves is necessary, but ***not sufficient***
- To earn a seat at the table, dynamic models must do at least as good a job of matching spectral evolution as ***spherical delayed detonation models => the new W7***
- Transition to detonation must be understood
- Spherical DD models are not complete
- No C, but O and Mg in same outer region. The entire progenitor must be burned for "core normal" SN Ia, deflagration models are ruled out
- How do we observationally discriminate between deflagration and delayed detonation models for subluminous SN Ia?
- MIR shows spectacular details, layering, ^{56}Ni "hole," Argon asymmetry

Summary

- Sample of 41 NIR spectra from SNe Ia
- Large sample size facilitates comparison to other data libraries – secondary parameters
- Spectra from normal SNe Ia show consistent evolution
- Burning products are layered – no mixing
- No C, but O and Mg in same region
- The entire progenitor must be burned
- DD models are favored
- Deflagration models are discouraged
- MIR shows spectacular details, layering, ^{56}Ni "hole," Argon asymmetry,