Modeling the After-Effects of Shocks Toward L1157

Andrew Burkhardt[1], Chris Shingledecker[1]
Brett McGuire[2], Niklaus Dollhopf[1], Eric Herbst[1]

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ISMS

1 U Virginia

2 NRAO

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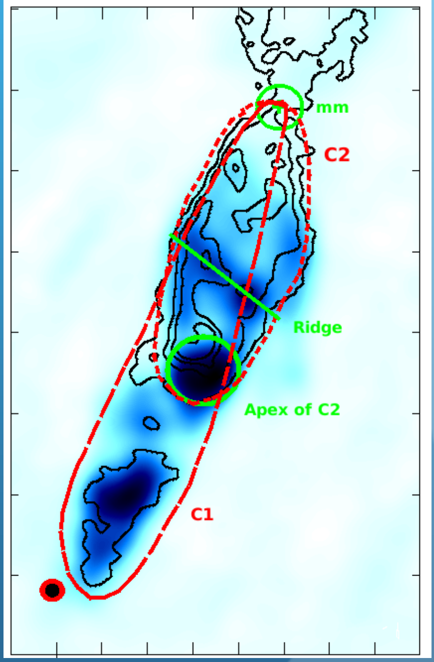
Observational Predictions

- Gas-phase CH_3OH can be significantly enhanced through the liberation off of grains
- The recent dynamic history of a source (e.g. recently shocked) may have an impact on the present shock-chemistry
  - 1st shock ➔ Liberation of complex species from ice
  - 2nd shock ➔ Destruction of complex gas-phase species and core erosion



(Burkhardt et al. 2016)

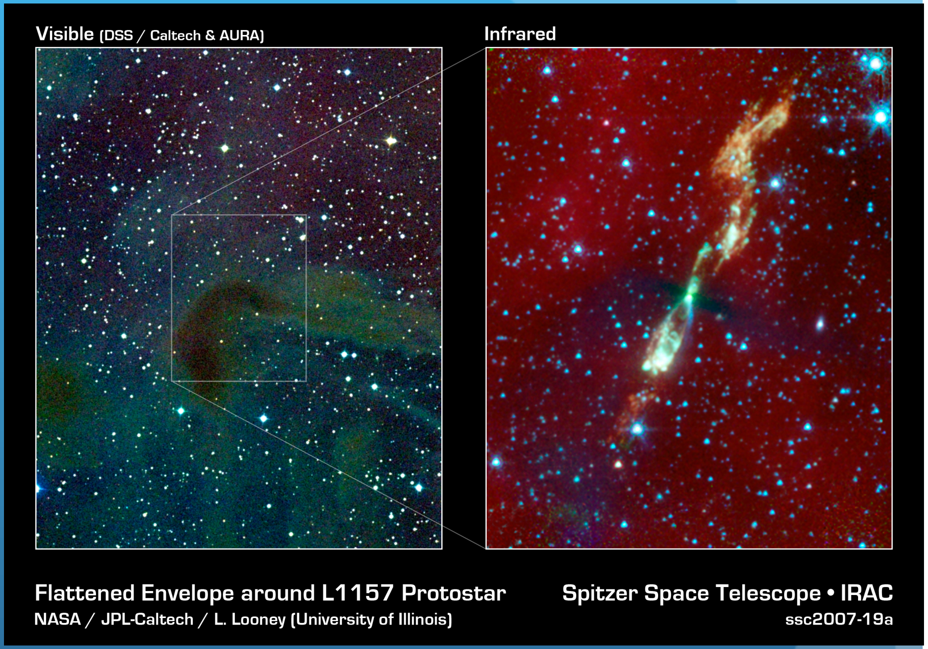
- Post-shock gas-phase chemistry may provide an astronomical “chemical clock,” due to high T & n
  - HNCO enhancement in O_2-rich post-shock gas

Shock Model Goals

- To accurately test predictions, model will incorporate:
  - NAUTILUS gas-grain chemical network code
  - High temperature chemical network, original version from Harada et al. 2010
  - Physical conditions of shocks
    - Time evolution of physical environment throughout shock
    - Sputtering processes
  - Dust heating in low-velocity shocks
- Once developed, can apply to various environments where shocks may be prevalent/significant

Why L1157?

- Prototypical "chemically -active" shocked outflow
- Prior to shock, surrounding material is believed to be cold, quiescent, and have pristine chemically-rich ice mantles



- Much simpler to model than other regions with a more complex physical history (Sgr B2, Orion KL, etc.)

NAUTILUS

- Fast 1D chemical network code solves sets of ODE's to compute abundances of species both in the gas-phase and grain-surface as a function of time (Hersant et al. 2009)
- Adapted from the original gas-grain model Hasegawa & Herbst (1993)
- Flexibility allows for incorporation of various changing physical parameters across time
- Model Outline:
  - Phase 1: Run standard dark cloud conditions to build up chemical complexity on ice (10 K, 5×10^4 cm^{-3})
  - Phase 2: Introduce shock(s) and allow propagation for 10^4 yr

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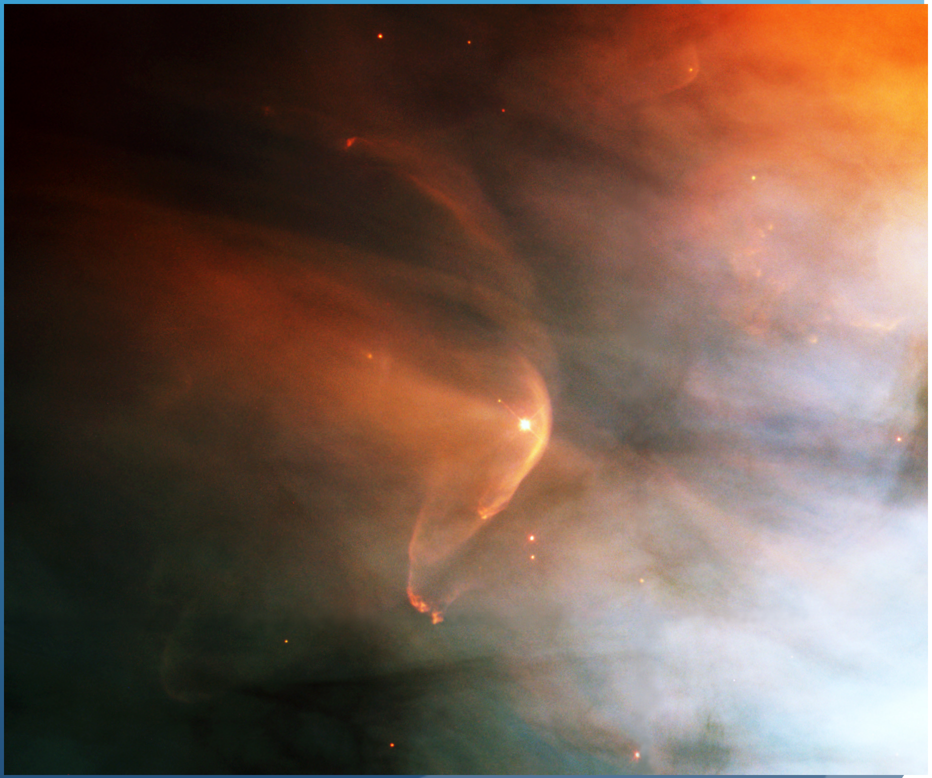
High Temperature Network

- To accurately describe the post-shock region, model requires reaction rates be accurate to T ~1000 K
- Adopt high temperature network originally developed by Harada et al. (2010), with contributions by Furuya, Acharyya, Hincelin, & others
- Contains ~8000 gas-phase & 2000 grain reactions and surface parameters for ~250 species



Describing Shocks - Evolution

- Parametric Treatment by Jiménez-Serra et al. (2008)
    - Parametric treatment allows for approximation of structure over chemically-relevant timescales
    - Input: v_s, T_0, n_0
    - Density and A_v scale appropriately with standard jump conditions
    - Approximate neutral temperature as Planck-like function

$$v_{\mathrm{n,i}} = (v_{\mathrm{s}} - v_0) - \frac{(v_{\mathrm{s}} - v_0)}{\cosh\left[(z - z_0)/z_{\mathrm{n,i}}\right]}$$

$$n_{\mathrm{n}} = \frac{n_0 v_{\mathrm{s}}}{v_{\mathrm{s}} - v_{\mathrm{n}}}$$

$$T_{\mathrm{n}} = T_0 + \frac{\left[a_T\,(z - z_0)\right]^{b_{\mathrm{T}}}}{\exp\left[(z - z_0)/z_{\mathrm{T}}\right] - 1}$$

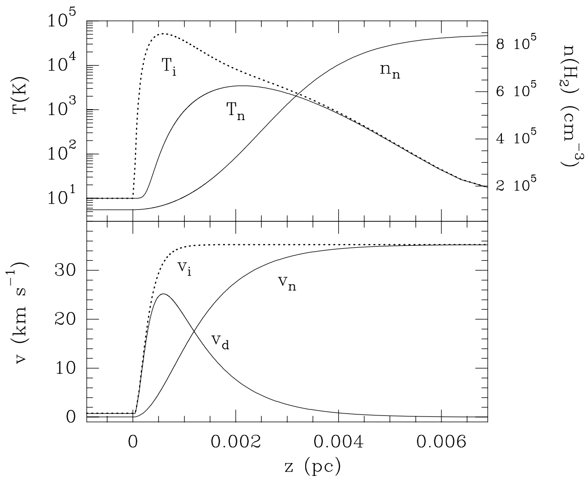


Fig. 3. C-shock physical structure obtained with Eqs. (1), (3), and (4) for $v_s = 40$ km s^{-1}, $n_0 = 10^5$ cm^{-3}, and $T_0 = 10$ K. Velocities are in the frame co-moving with the preshock gas. The magnetic precursor length is of $\Delta z \sim 0.0005$–0.001 pc = 1.5–3.0×10^{15} cm.

Describing Shocks - Sputtering

- Sputtering necessary to describe non-thermal desorption processes crucial for shock-chemistry
- Again, following formalism of Jiménez-Serra et al. (2008)
    - Sputtering rate a function of the collisional rate of a given gas-phase particle to strike a target and the sputtering yield of target by projectile with velocities large enough to cause desorption
    - Given surface parameters for each grain species, can calculate sputtering rate due to all major gas-phase particles, which have been determined by NAUTILUS

$$\left[\frac{\mathrm{d}n(\mathrm{CH_3OH})}{\mathrm{d}t}\right]^{\mathrm{m}}_{\mathrm{tot}} = n_{\mathrm{g}}\, r_{\mathrm{m}} \left[\frac{\mathrm{d}n(\mathrm{CH_3OH})}{\mathrm{d}t}\right]^{\mathrm{m}}_{\mathrm{grain}}$$

$$\left[\frac{\mathrm{d}n(m)}{\mathrm{d}t}\right]_{\mathrm{grain}} = \pi a^2 n_{\mathrm{p}} \left(\frac{8kT_{\mathrm{n}}}{\pi m_{\mathrm{p}}}\right)^{1/2} \times \frac{1}{s}\int_{x_{\mathrm{th}}}^{\infty} \mathrm{d}x\, x^2\, \frac{1}{2}\left[\mathrm{e}^{-(x-s)^2} - \mathrm{e}^{-(x+s)^2}\right]\langle Y(E)\rangle_{\theta}$$

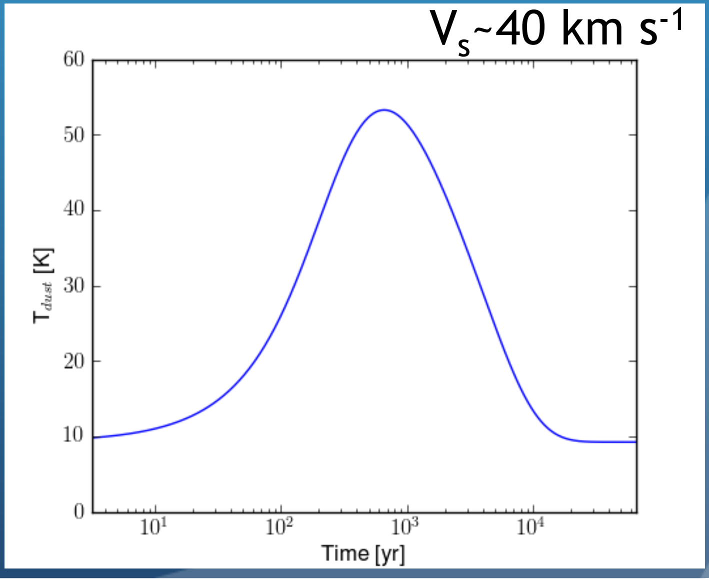
$$Y(E, \theta = 0) = A\frac{(\varepsilon - \varepsilon_0)^2}{1 + (\varepsilon/30)^{4/3}}, \quad \varepsilon > \varepsilon_0,$$

Dust Heating

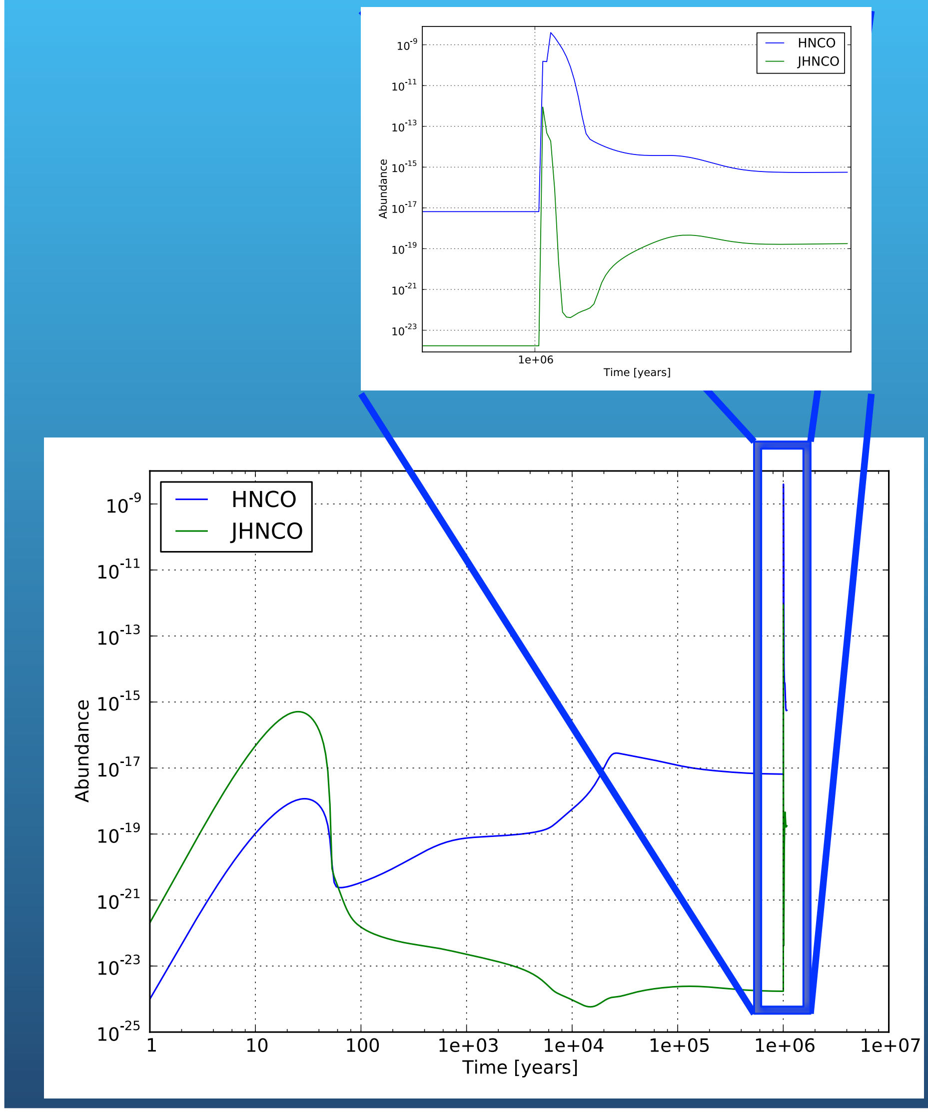
- Dust temperature evolution is crucial for understanding the post-shock environment to understand rate of reproduction of ice mantles
- Dust temperature throughout the shock: (Aota et al. 2015)
  - Heating = collisional heating from gas particles
  - Cooling = thermal radiation

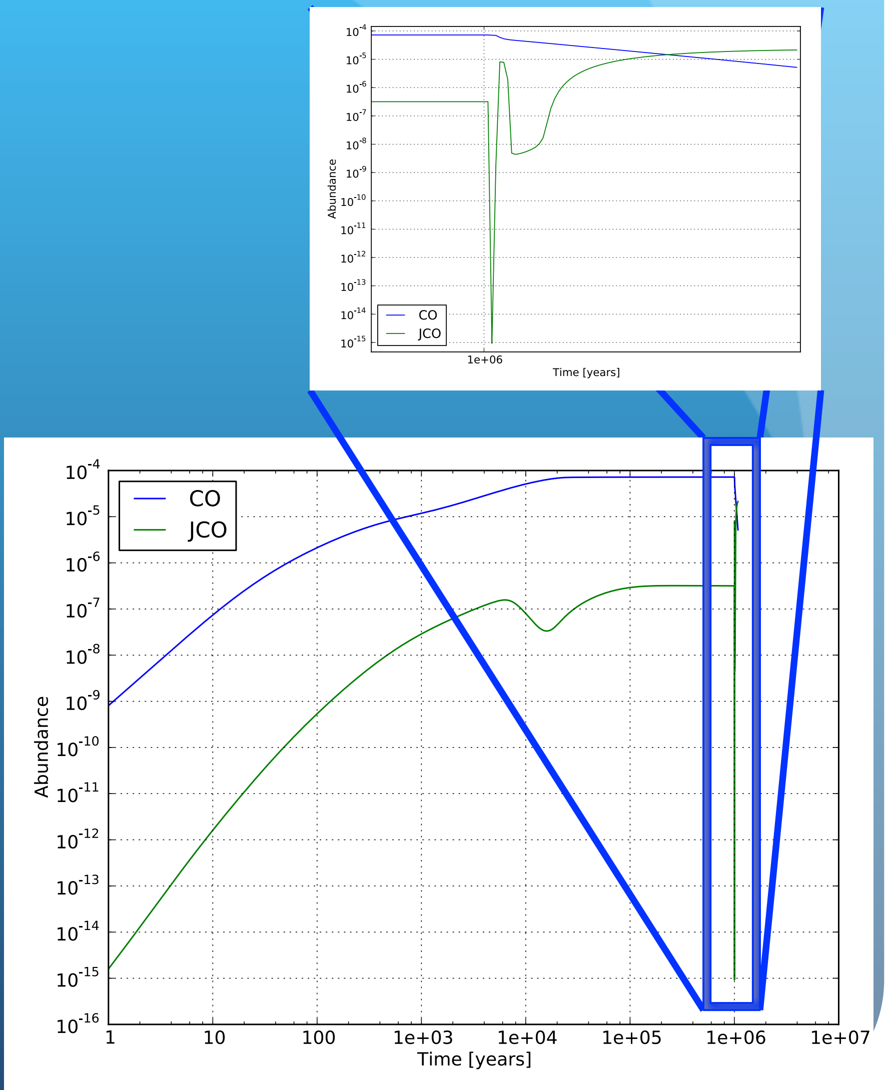
$$\pi a_{\rm dust}^2 v n_{\rm gas} \left(\frac{1}{2} m_p v^2\right) = 4\pi a_{\rm dust}^2 \epsilon \sigma_{SB} T_{\rm dust}^4 .$$

$$T_{\rm dust} \sim 14 \left(\frac{v}{1\,{\rm km\,s^{-1}}}\right)^{0.5} \left(\frac{n_{\rm H_2}}{10^6\,{\rm cm^{-3}}}\right)^{1/6} [K].$$


V_s~40 km s^{-1}

Example Simulations





Moving Forward

- Once complete, will be able to:
    - Reproduce enhanced abundances observed in L1157
    - Test time evolution of shock-enhanced species like HNCO
    - Study effects of multiple shocks on molecular enhancements
- Once able to reproduce L1157 observations, should be able to apply model to study more complex regions
- Shocks may prove to be transient phenomena that are crucial for accounting for unexplained overabundances observed compared to theoretical predictions

Thanks

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Invited Talks & Speakers

Galaxy Formation and Evolution I: Cosmic Evolution (Caitlin Casey)
Galaxy Formation and Evolution II: Gas & Star Formation Properties (Linda Tacconi)
Galactic Centers: Star Formation, AGN, Black Holes & ULIRGs (Masatoshi Imanishi)
Nearby Galaxies I: Normal Galaxies (Karin Sandstrom)
Nearby Galaxies II: Starburst & Super Star Clusters (Kazushi Sakamoto)
Massive Star Formation (Jill Rathborne)
Low Mass Star Formation (Adele Plunkett)
Chemical Evolution During Star and Planet Formation (Jeong-Eun Lee)
Protostellar Disks & Planet Formation (Laura Perez)
Debris Disks (Brenda Matthews)
Stars and Stellar Evolution (Leen Decin)
Solar System (Arielle Moullet)
Synergy between ALMA and JWST (Klaus Pontoppidan)
ALMA after 5 Years (Pierre Cox)
Future ALMA (John Carpenter, Al Wootten, Neal Evans)
Conference Summary (Anneila Sargent)