# Abundant $SO_2$ Gas in the Hot Core around MonR2 IRS3

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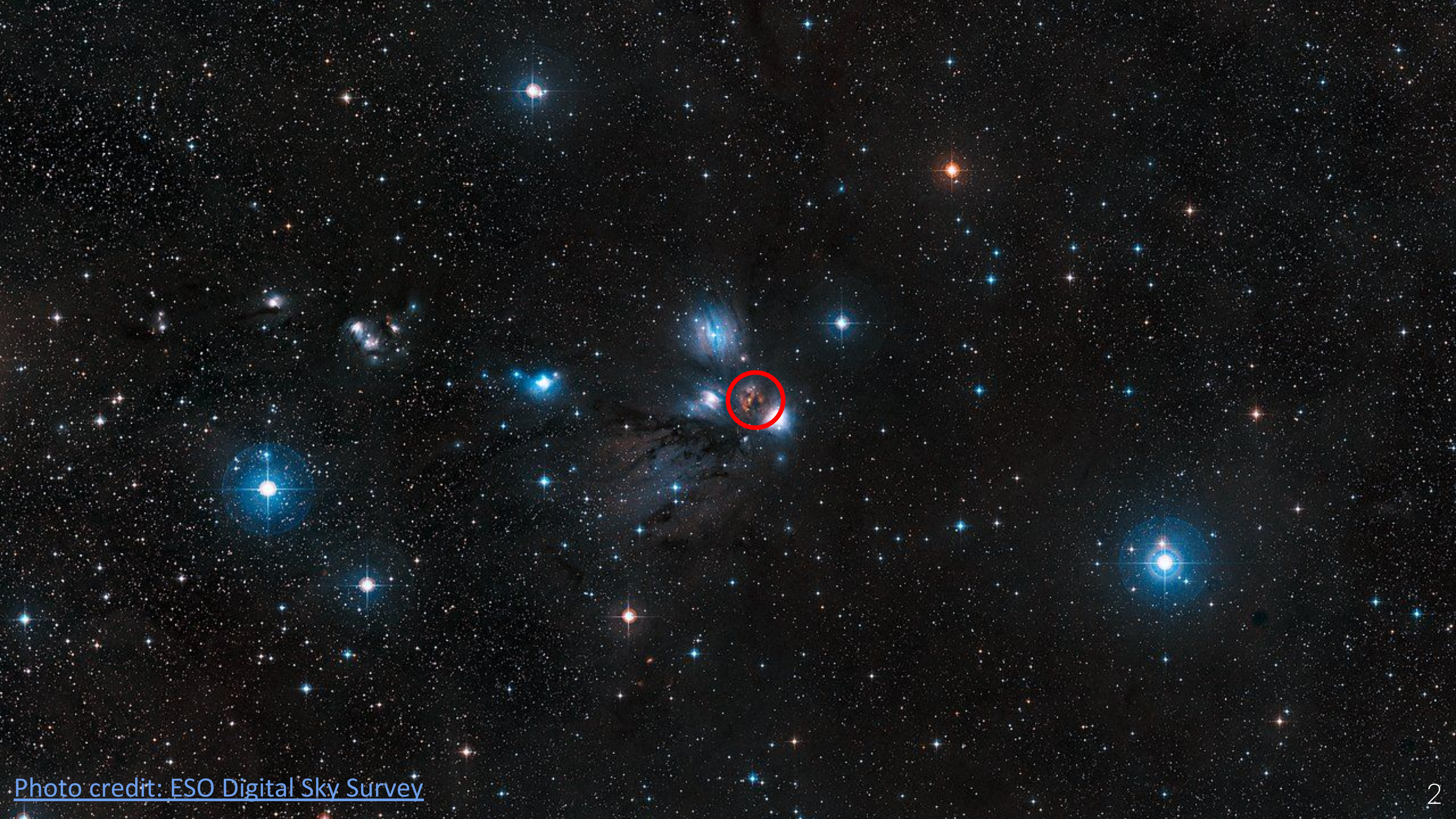


Photo credit: ESO Digital Sky Survey

# Sulfur Budget Problem

- Sulfur is the 10th most abundant element in the universe
  - From observations of HII regions, the solar photosphere, and the diffuse interstellar medium (ISM)
- Dense clouds are severely depleted
  - Abundances as low as 5% of the cosmic value
- So where does it all go?
  - Gas-phase molecules, refractory dust grains, and icy mantles
  - A wide-variety of molecules have been observed in sub-millimeter wavelengths but only in very small abundances

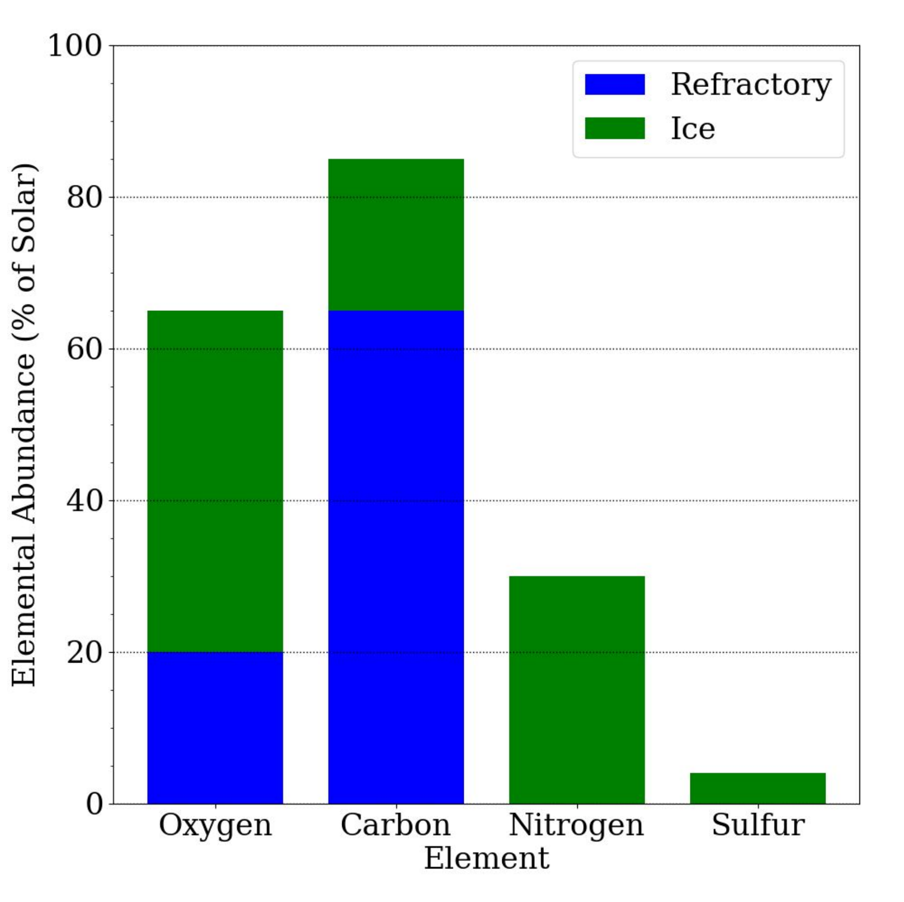



Fig. 1: Fraction of an Element's cosmic abundance that is accounted for

# Why do we care?

- Sulfur has an extremely rich and diverse chemistry
  - Sulfur can easily imitate oxygen in just about any molecule: e.g., ethanol ($C_2H_6O$) and ethanethiol ($C_2H_6S$)
  - Sulfur is second to only carbon in the number of allotropes it has
- Sulfuretted molecules can be used for a variety of purposes
  - Tracers of evolution in protostellar environments (i.e., chemical clocks)
  - Connect primitive solar system objects with conditions in the protosolar envelope
  - Sulfur is necessary for life as we know it

# How do we chip away at this?

- We focus on $SO_2$ specifically, one of the simpler sulfuretted molecules
    - $SO_2$ is one of the three molecules thought to be useful in the "chemical clocks" approach to measuring hot core age
    - $SO_2$ measurements in the mid-infrared and sub-millimeter find differing abundances
    - $SO_2$'s formation pathway is not well understood

# Invisible to the eye

- Sub-millimeter observations
    - Lower resolution only probes the colder broader gas around these objects
- Mid-infrared wavelengths enable two possibilities
    - Ice-phase observations
        - Have proven very difficult, yielding non-detections or very low abundances
    - Warm gas-phase absorption
        - Allow us to directly probe the chemistry of the hot core itself

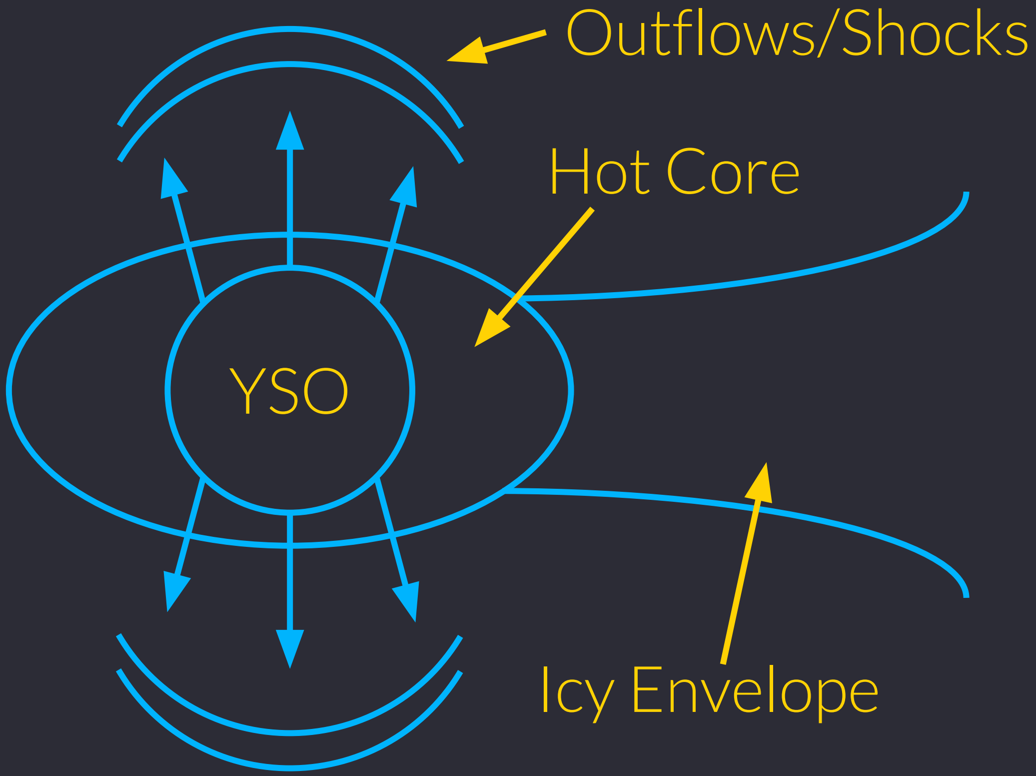
# Observations: Past...

- Sub-millimeter emission from the gas-phase $SO_2$ (van der Tak et al. 2003)
  - Yields a very low abundance (roughly 0.1% the cosmic sulfur abundance)
- Mid-infrared absorption (previously done by Infrared Space Observatory, Keane et al. 2001)
  - Indicate a much higher abundance (by over 2 orders of magnitude) $SO_2$ gas in the hot core
  - Leads us to the question, where does it come from?

# Observations: ... & Present

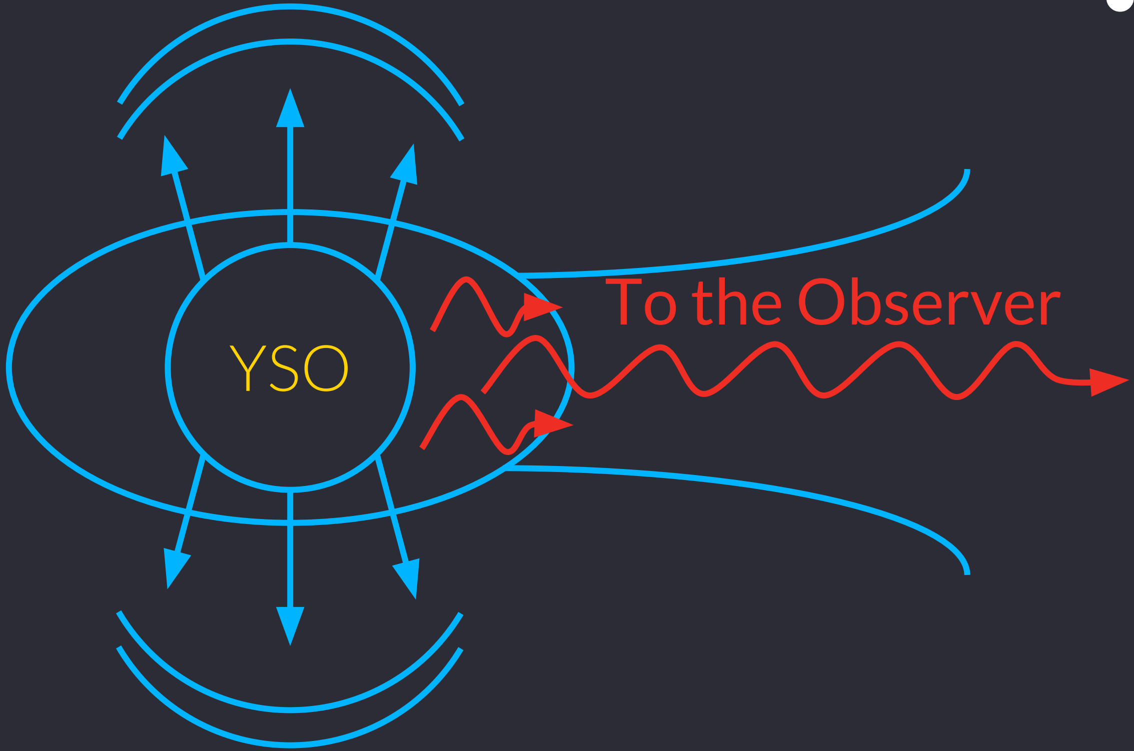
- We use the Echelon-Cross-Echelle Spectrograph (EXES) for $SO_2$
  - Gas-phase absorption at high resolution (R of 55,000)
  - Covers a band around 7.3 μm
  - High R is the key, it allows us to resolve individual lines
- We also have Keck NIRSPEC observations for CO to determine relative abundances
  - Gas-phase absorption at medium resolution (R of 25,000)
  - M-band spectra

# Hot Cores




- Envelope of warm, dense gas around a young stellar object
    - Ices have evaporated
- These conditions lead to a rich chemistry

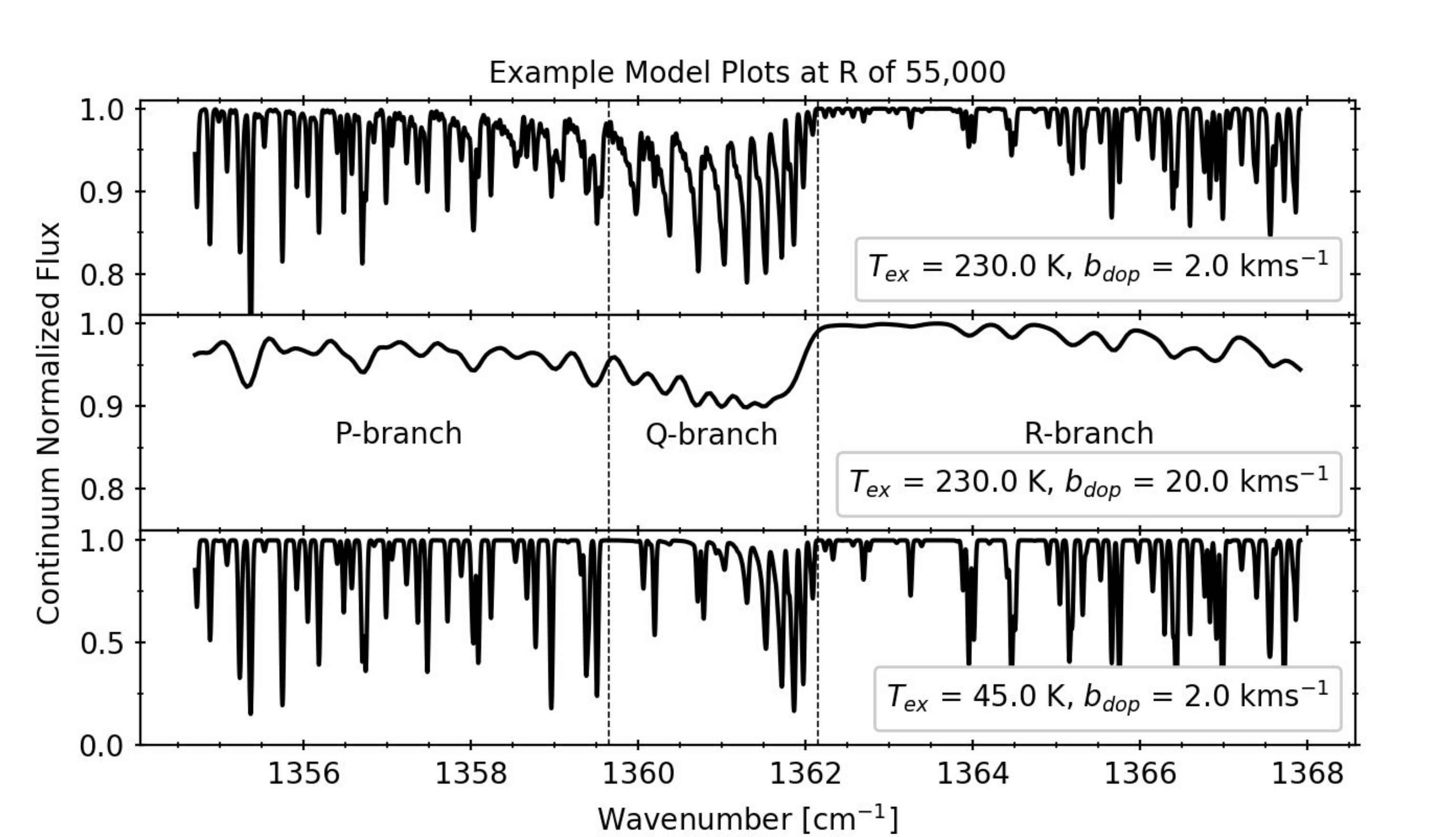
# What the Sub-mm missed




- Absorption along line of sight allows us to probe the region closest to the young stellar object (YSO)

# LTE Models

- We generate model spectra through a local thermodynamic equilibrium (LTE) model
  - Three input parameters: Excitation Temperature ($T_{ex}$), Column Density ($N_{col}$), and Doppler Parameter ($b_{dop}$)
- Likelihood is computed by using a $\chi^2$ value
  - Best fit is chosen by minimization
  - Error bars are found by Monte Carlo Markov Chain sampling to determine the likelihood distributions for each input parameter




# Fig. 2: Example LTE Models for $SO_2$

# Best Fit

- $SO_2$ gas with a temperature of 234±15 K
    - We call this the warm component, our data only allowed for upper limits on the cold foreground component
- Warm $SO_2$ abundance limit of $SO_2/H > (5.6±0.5)x10^{-7}$
    - Accounts for >4% of the cosmic S abundance
    - Limit due to lower resolution of CO data
- Linewidth of $b < 3.20$ km $s^{-1}$
    - On the edge of being resolved by the instrument

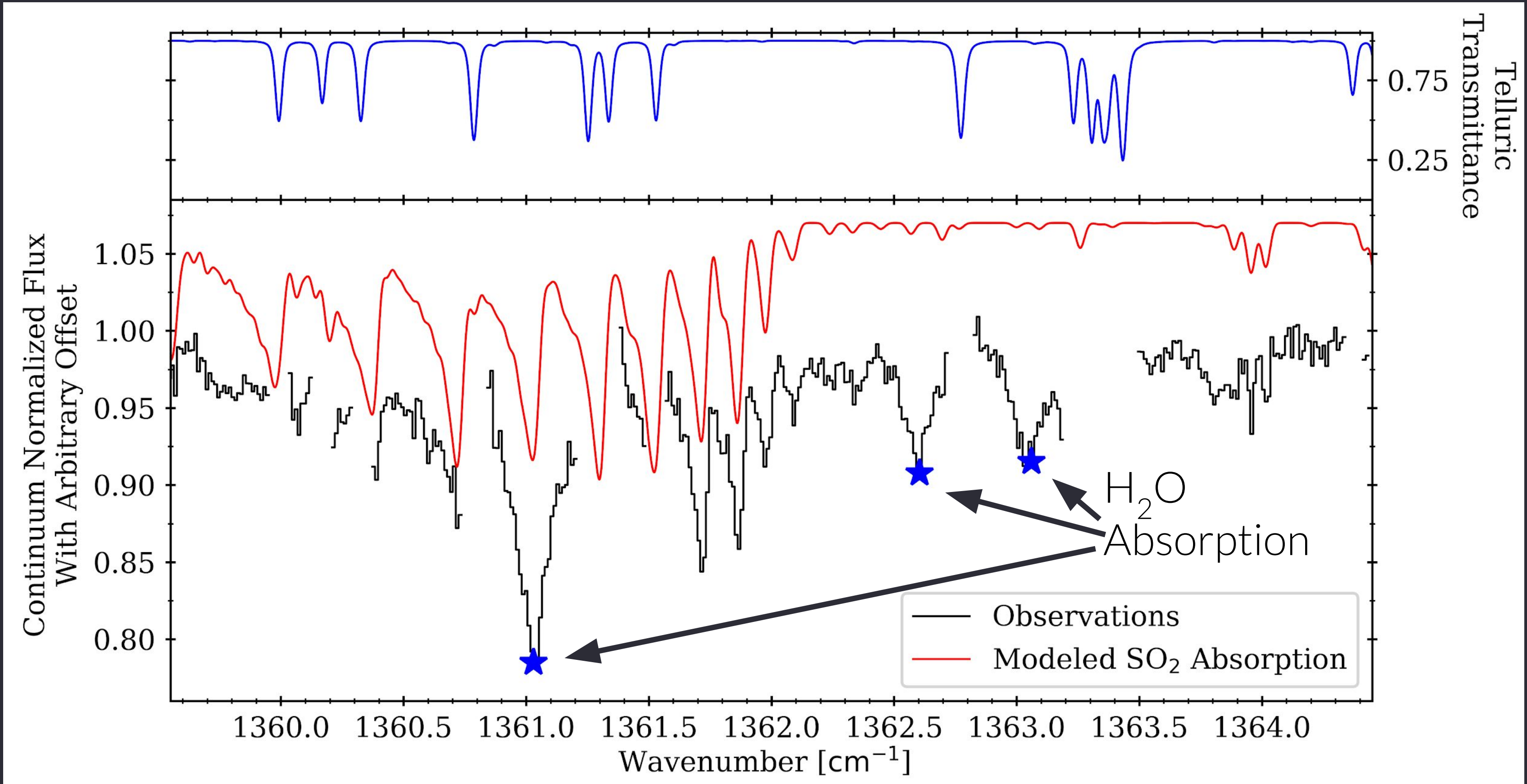



Fig. 3a: Subset of $SO_2$ Spectrum with Best Fit

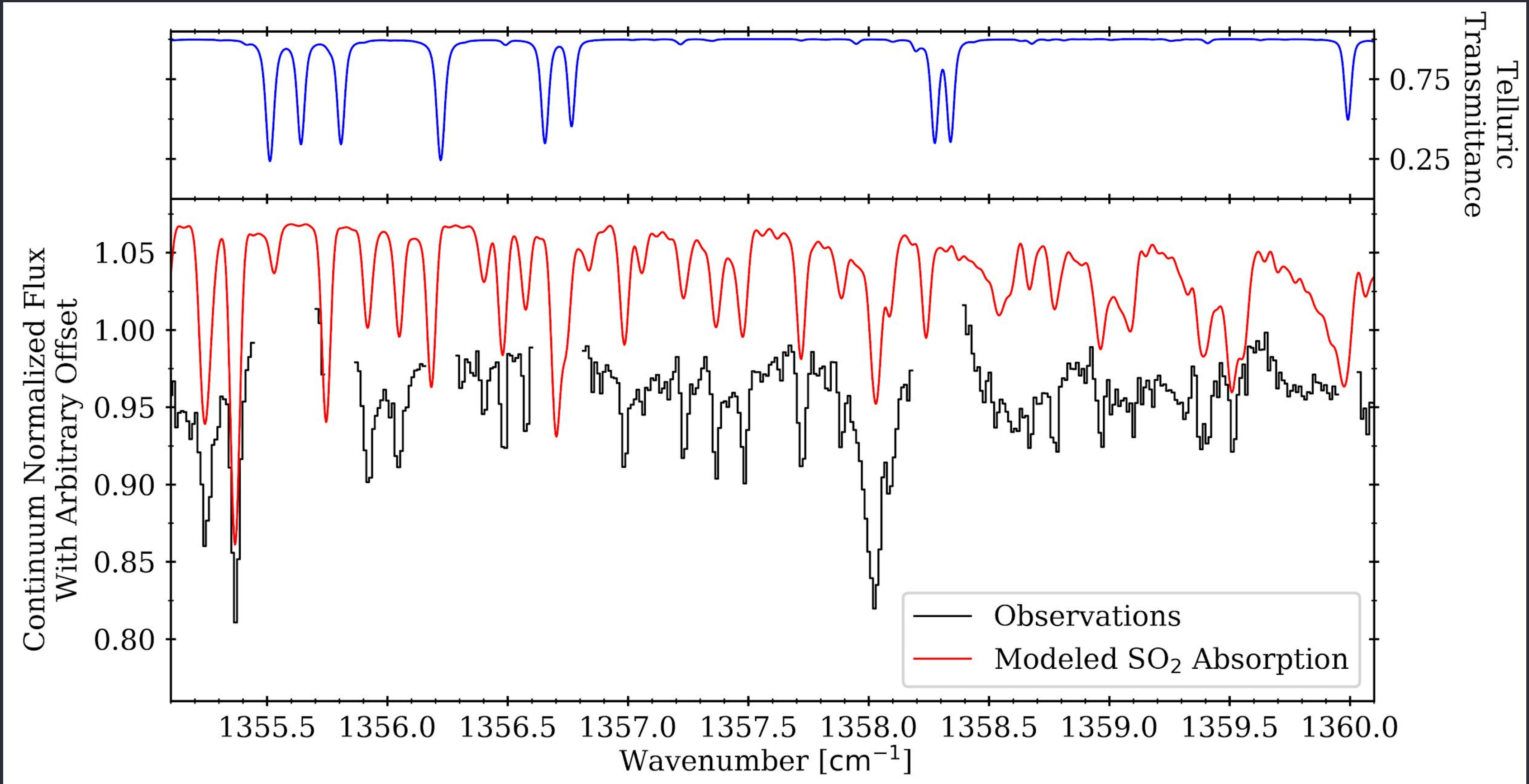
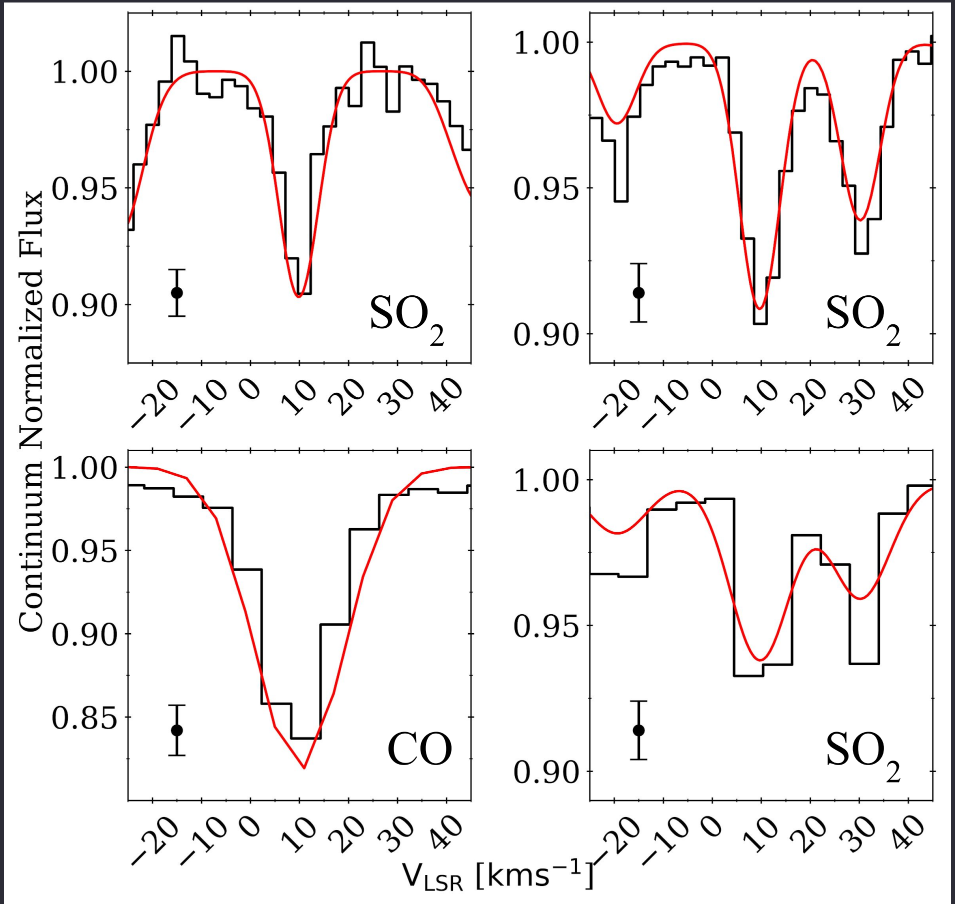



Fig. 3b: Subset of $SO_2$ Spectrum with Best Fit

Model + Data w/ R = 55,000

Model + Data w/ R = 25,000



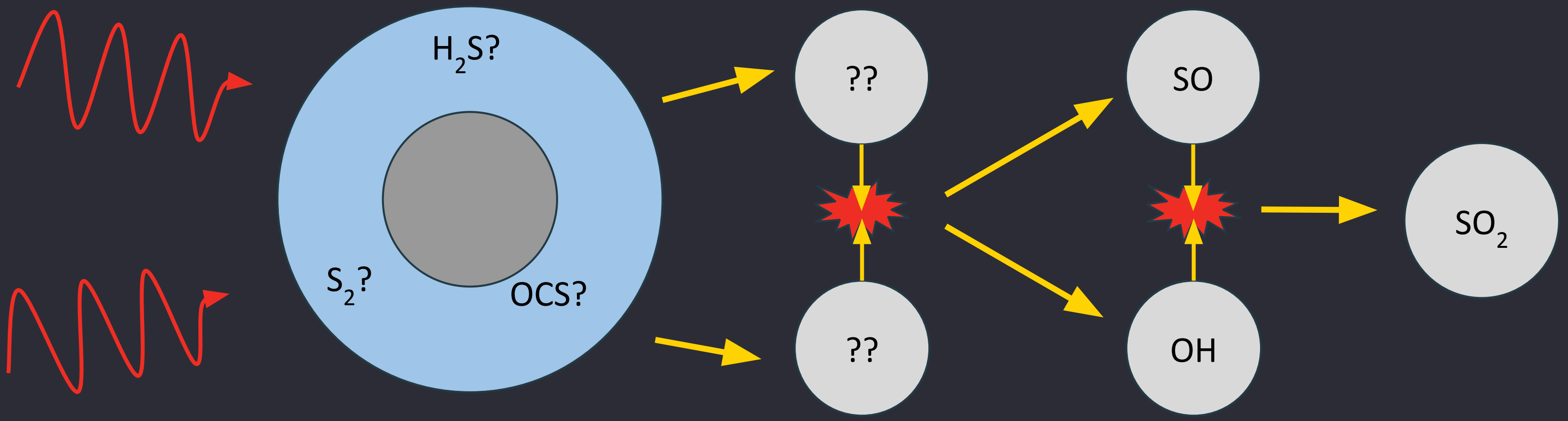

Model + Data w/ R = 55,000

Model + Data w/ R = 25,000

# Fig. 4: Line Profiles

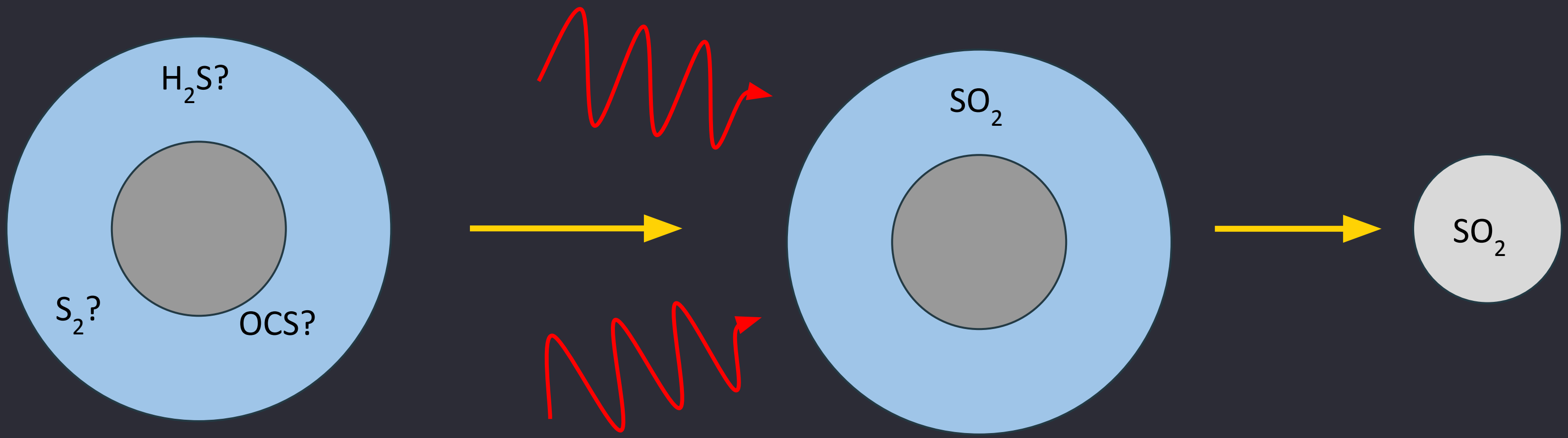
# Origin of SO2: Radiative Heating

- Gas-phase formation: sulfuretted ices sublimate before forming $SO_2$
  - Expect high temperatures due to location in hot core
  - Expect narrow linewidths due to quiescent gas



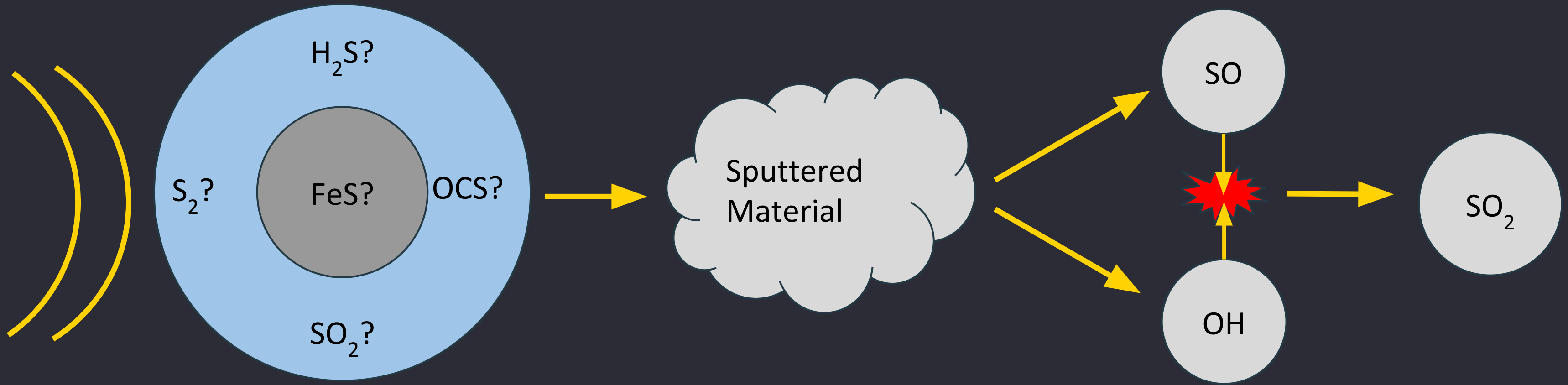
# Origin of SO2: Radiative Heating

- Ice-phase formation: sulfuretted ices evolve into an $SO_2$ ice before sublimating
  - Expect high temperatures due to location in hot core
  - Expect narrow linewidths due to quiescent gas



# Origin of SO2: Shock heating

- Gas-phase formation: sulfur locked in the dust is released enabling gas-phase formation
  - Expect low temperatures due to rapid post-shock cooling
  - Expect broad linewidths due to shock wave passing through gas



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**Consistent with a radiative heating picture**

# Radiative vs Shocks

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  - We call this the warm component, our data only allowed for upper limits on the cold foreground component
- Warm $SO_2$ abundance limit of $SO_2/H > (5.6 \pm 0.5) \times 10^{-7}$
  - Larger than that derived for Orion IRc 2 ($2 \times 10^{-7}$; Blake et al. 1987)
  - Consistent with that of HH 212 ($4–12 \times 10^{-7}$; Podio et al. 2015)
- Linewidth of $b < 3.20$ km $s^{-1}$
  - On the edge of being resolved by the instrument

**Hot core formation of $SO_2$ is at least as efficient as shock formation**

# Ice-phase vs Gas-phase

- Ice-phase $SO_2$ measurements find extremely low abundances
  - The ice-phase $SO_2/H_2O$ abundance is $0.6\times10^{-2}$ *
  - The warm gas-phase $SO_2/H_2O$ abundance is $(10.0\pm3.0)\times10^{-2}$
- Mismatch between ice-phase and warm gas-phase abundances **implies $SO_2$ can not be sublimating directly from the ice**

*Calculated with values from Zasowski et al. 2009 ($SO_2$) and Gibb et al. 2004 ($H_2O$)

# Then what's in the ice?

- $H_2S$ is the chemical model's molecule of choice
  - $H_2S$ is the dominant sulfur-bearer (roughly 60%) in comets (Calmonte et al. 2016)
  - $H_2S$ ice measurements are, at best, upper limits, and half the abundance we measure for warm $SO_2$ gas
- We believe the ice must be releasing sulfur allotropes
  - Sulfur allotropes are the next largest sulfur-bearer in comets
  - They are also highly volatile, leading to sublimation at low temperatures
  - Difficult to observe

# Future work

- Higher resolution CO data with iShell
  - Data has been collected and reduced, awaiting analysis
- More targets
  - W3 IRS5, data collected and mostly reduced
    - Problems with standard star introduced excess noise in $SO_2$ data

# Conclusions

- $SO_2$ in Mon R2 IRS 3 is consistent with a radiative heating model
- The hot core formation of $SO_2$ is at least as efficient as the shock formation
- $SO_2$ is unlikely to be forming in the ice
- Sulfur allotropes may be required to explain sulfur chemistry in molecular clouds

# References


[Blake et al. 1987]

[Calmonte et al. 2016]

[Gibb et al. 2004]

[Keane et al. 2001]

[Podio et al. 2015]

[van der Tak et al. 2003]

[Zasowski et al. 2009]