Molecular Tracers of Turbulent Shocks in Molecular Clouds

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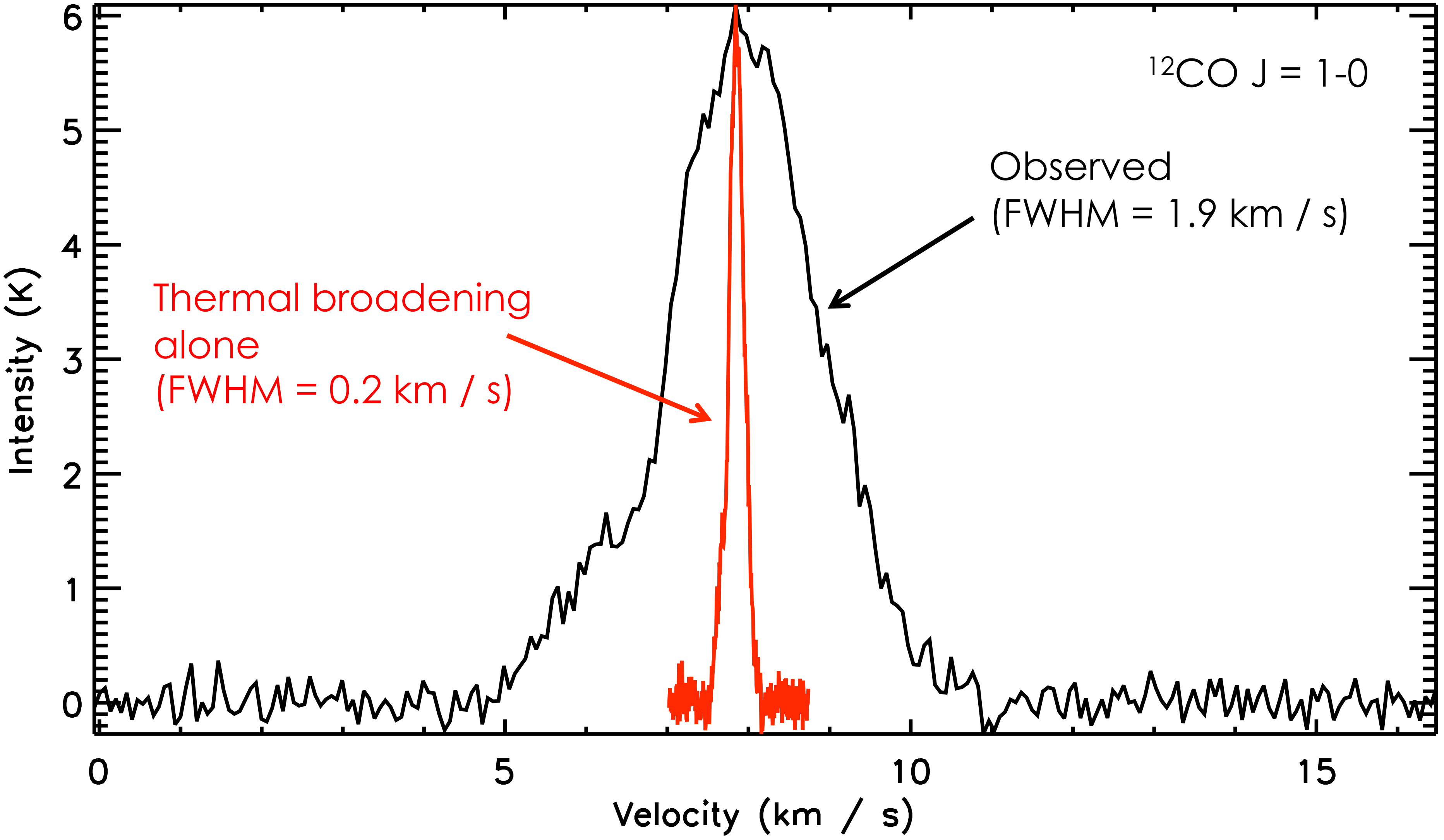
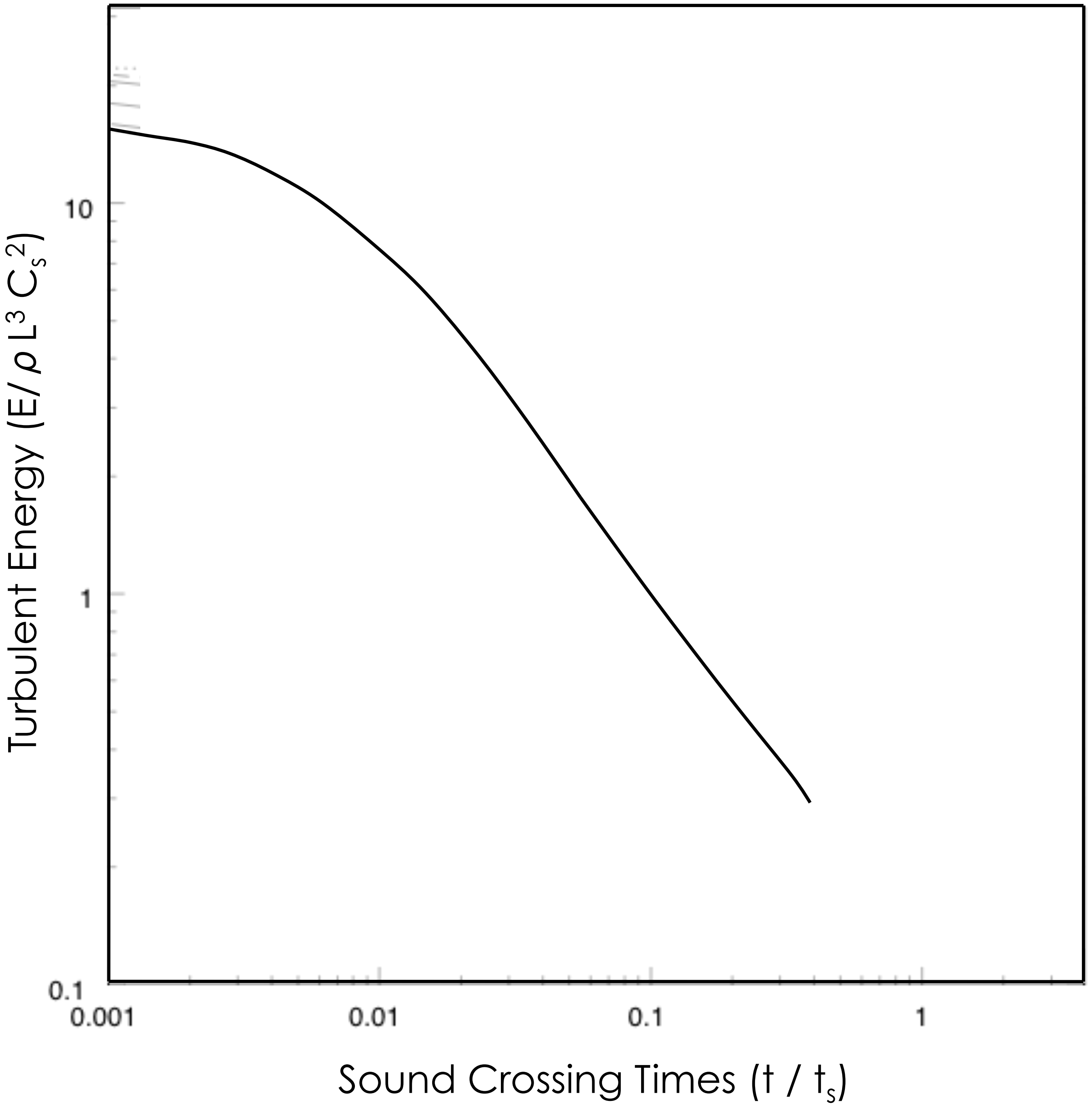


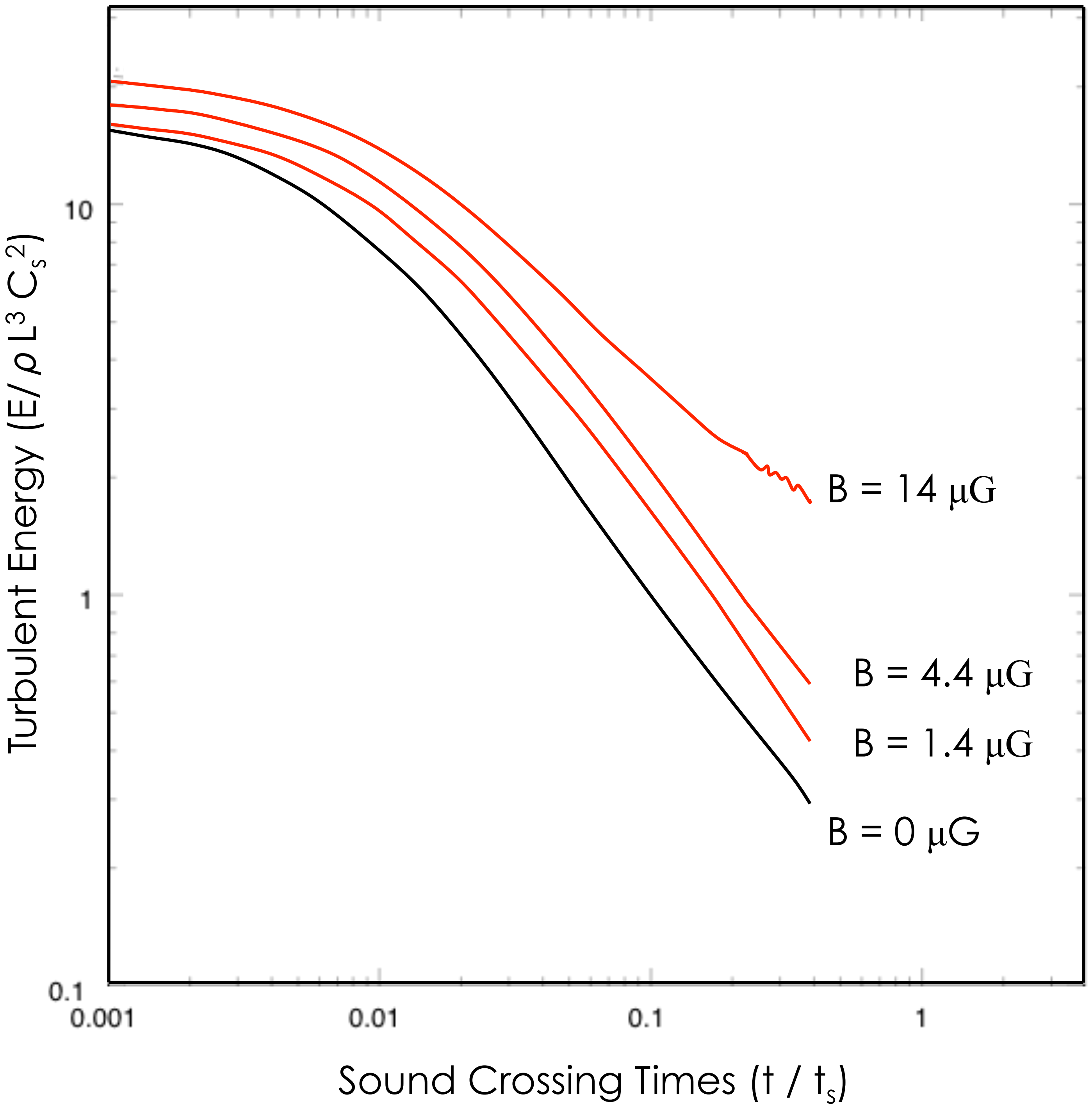
Ridge et al. (2006)

Turbulent Energy Decay in a Hydro Simulation



Stone et al. (1998)

Turbulent Energy Decay in MHD Simulations



Stone et al. (1998)

Shock Model Setup

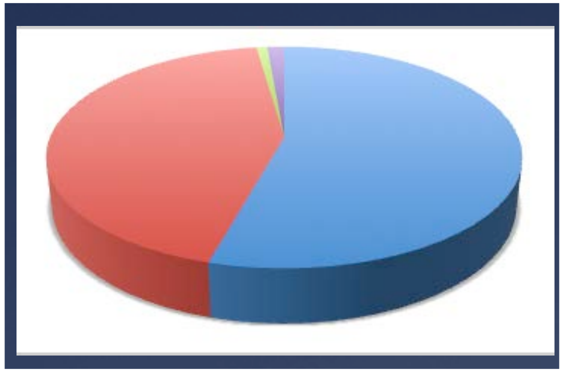
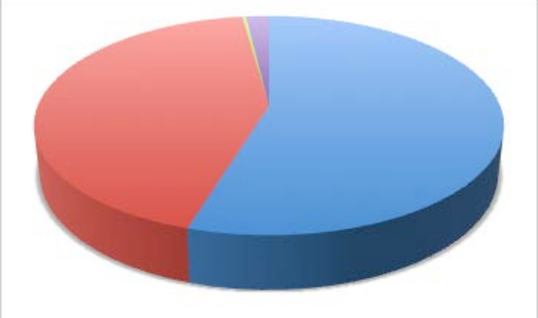
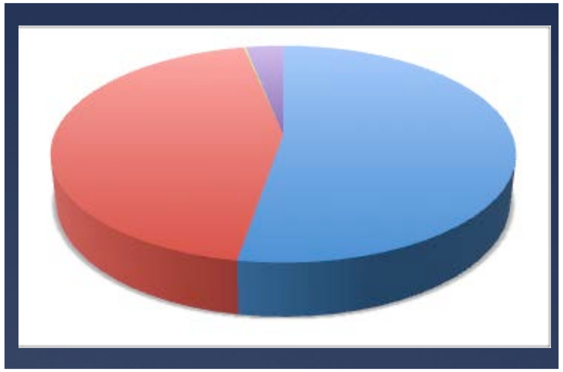
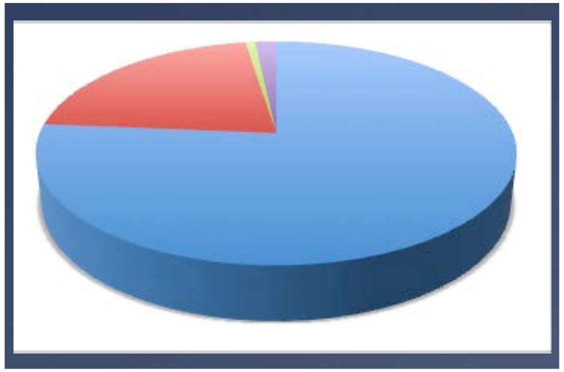
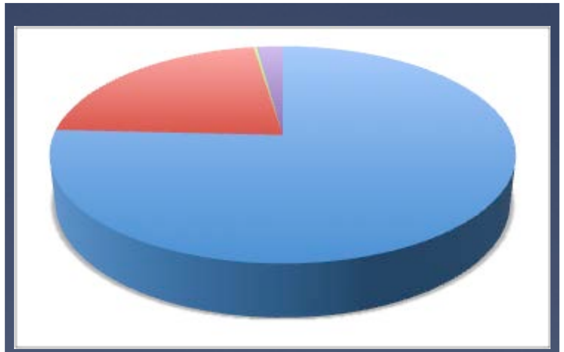
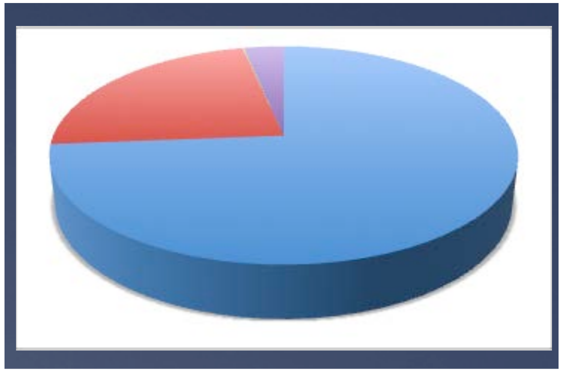
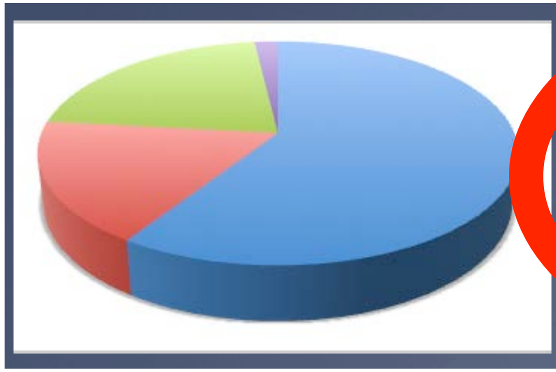
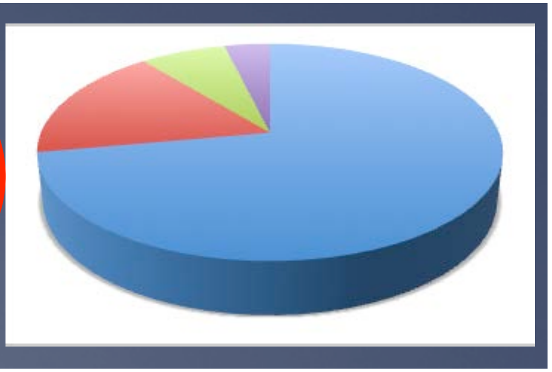
- Magnetohydrodynamic (MHD) C-shock code from Kaufman & Neufeld (1996)
- Density of either $10^{2.5}$, 10^3 or $10^{3.5}$ cm^{-3}
- Shock velocities of 2 or 3 km / s
- Initial magnetic field strengths, perpendicular to the shock direction, of $B = b\ n(H)^{0.5}$ μG, where b = 0.1 or 0.3. This gives B from 3 μG to 24 μG.
- Mach numbers from 10 to 20 and Alfvénic Mach numbers ranging from 5 to 15

🟦 CO

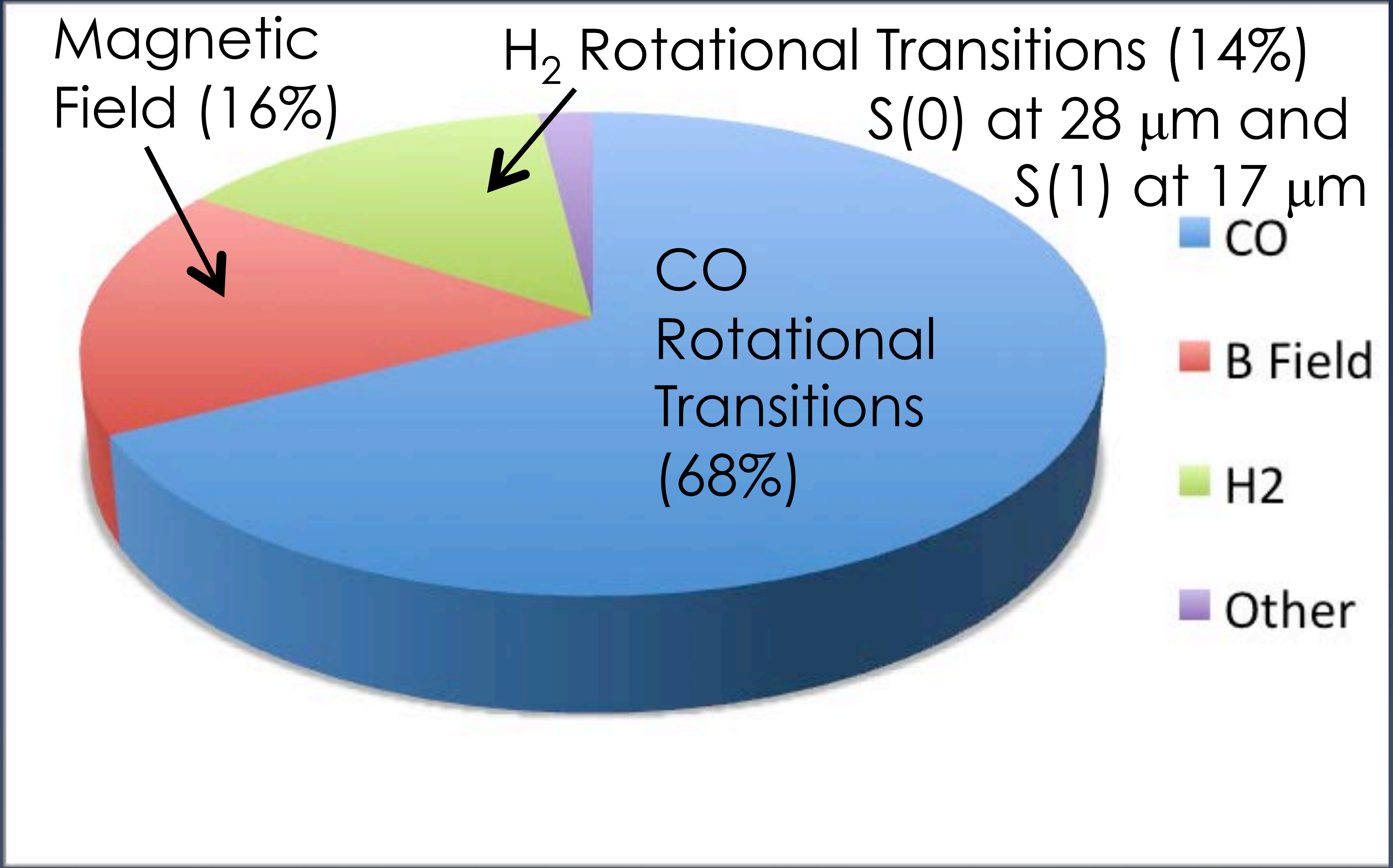
🟥 B Field

🟩 H2

🟪 Other

	n = $10^{2.5}$ cm^{-3}	n = 10^{3} cm^{-3}	n = $10^{3.5}$ cm^{-3}
v = 3 km s^{-1} b = 0.3			
v = 2 km s^{-1} b = 0.1			
v = 3 km s^{-1} b = 0.1			

Energy Dissipation Mechanisms



Magnetic Field (16%)

H_2 Rotational Transitions (14%)
S(0) at 28 μm and
S(1) at 17 μm

CO Rotational Transitions (68%)

Molecular Cloud Dissipation Rate

The turbulent energy density is:

$$E = 3/2\ \rho v^2$$

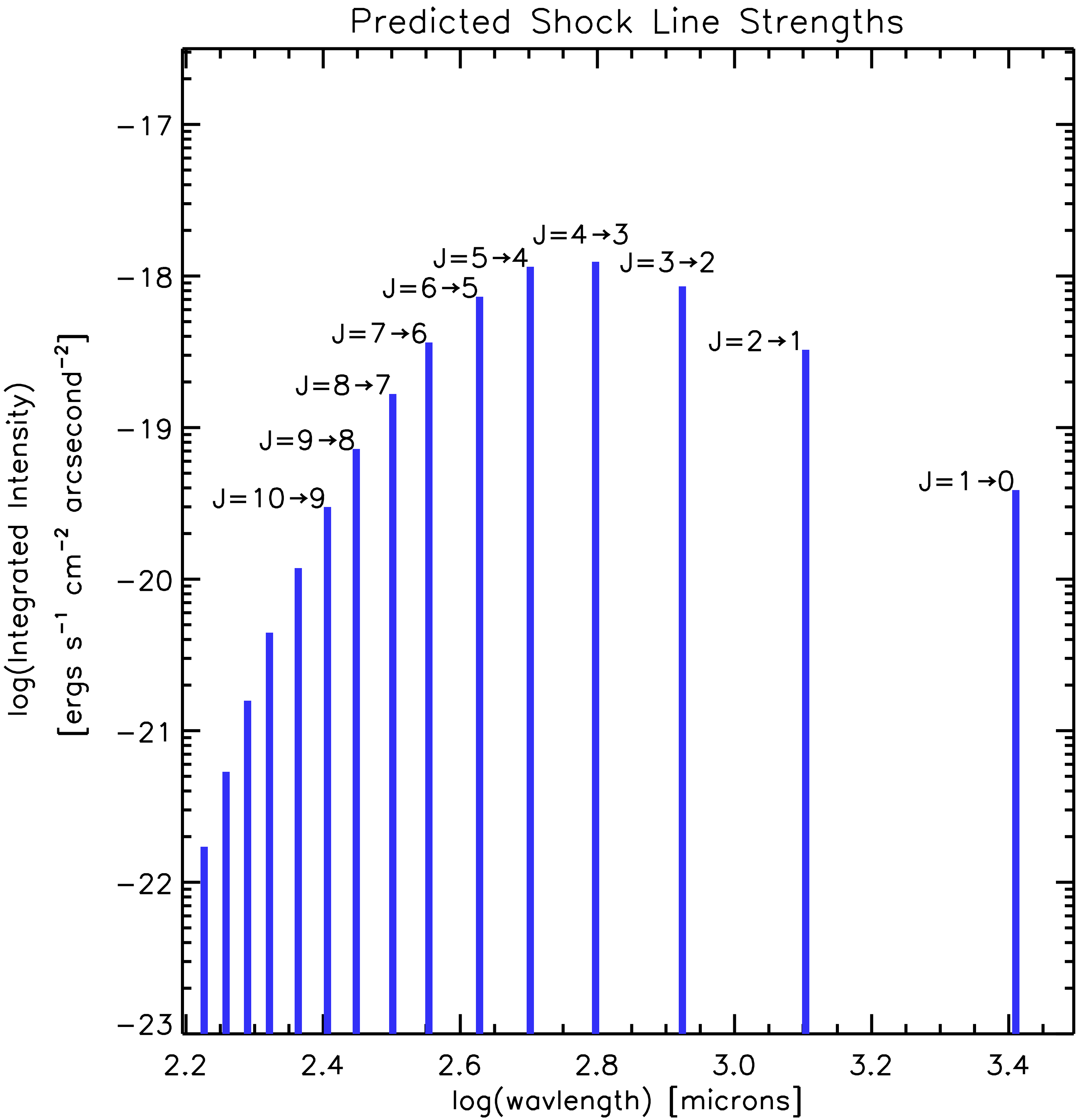
If the dissipation timescale is roughly the crossing time:

$$\Delta E / t_c = 3/2\ \rho v^2 * v / (2R)$$

There is an empirical relationship between the velocity dispersion and the radius of a molecular cloud.

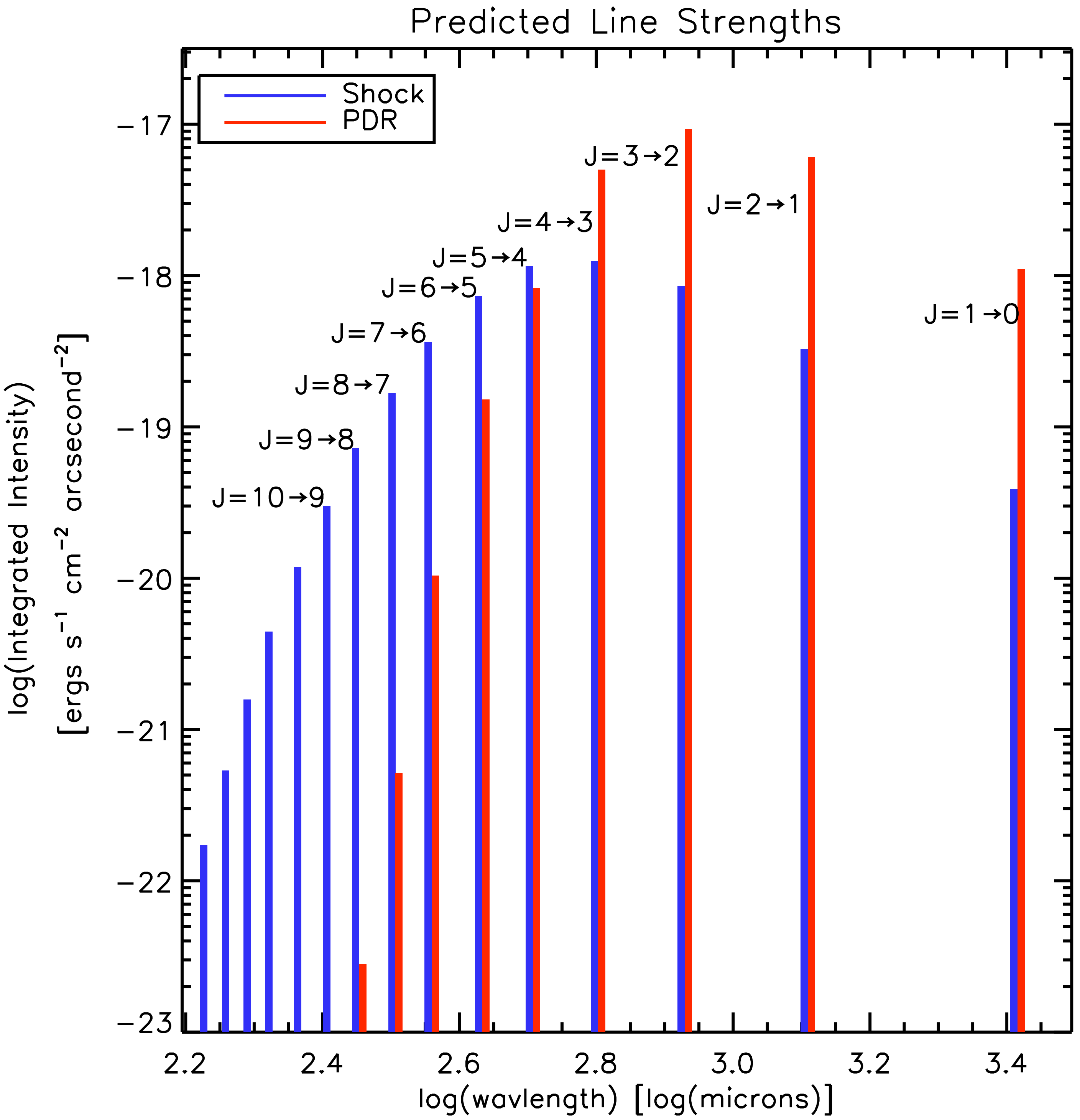
For a spherical cloud:

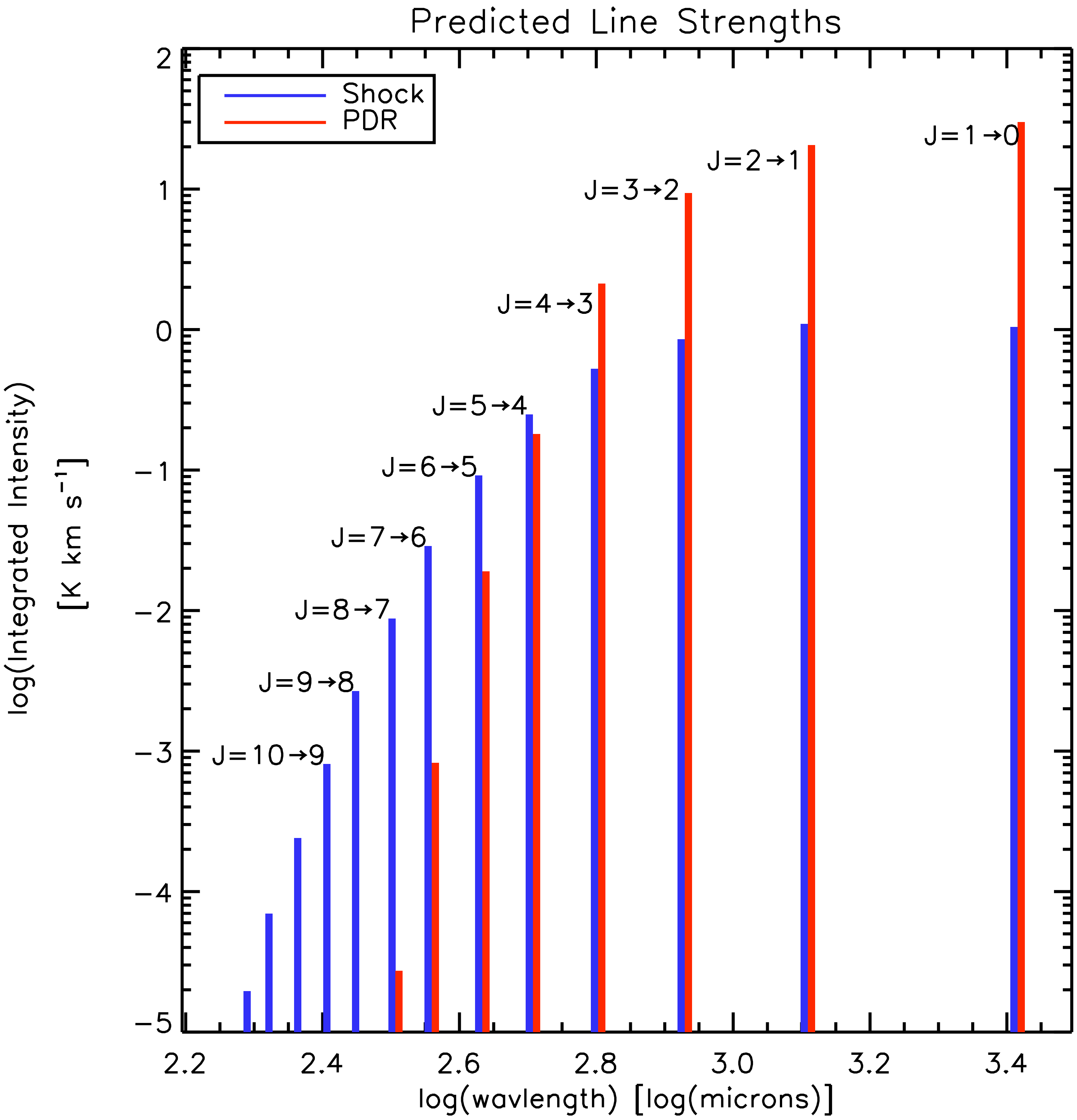
$$\mathbf{L_{turb} = 5.12 \times 10^{32} \left(\frac{n}{1000cm^{-3}}\right) \left(\frac{v}{km\,s^{-1}}\right)^{7} ergs\,s^{-1}}$$

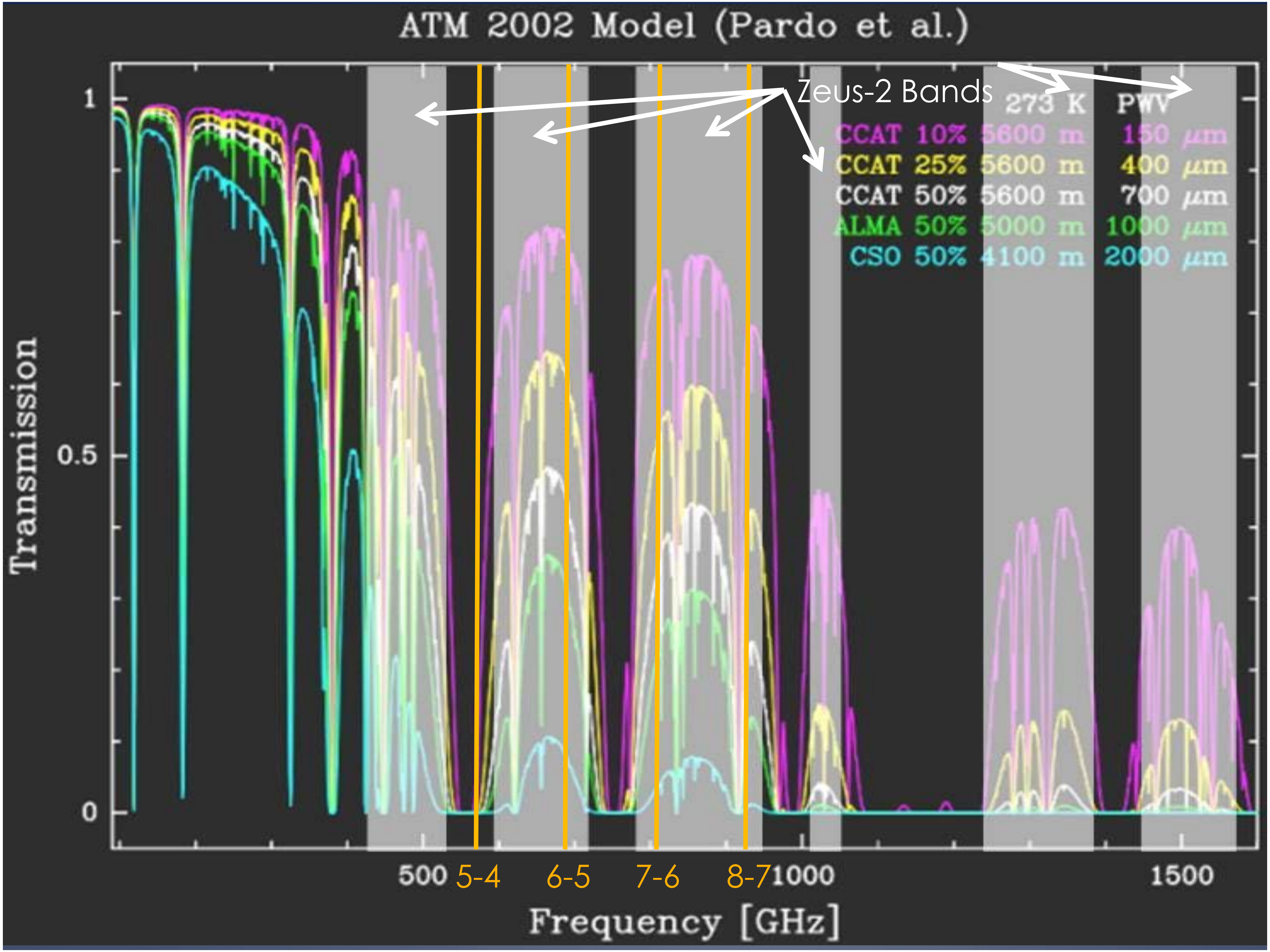

Predicted Shock Line Strengths
log(Integrated Intensity)
[ergs s^{-1} cm^{-2} arcsecond^{-2}]
−17
−18
−19
−20
−21
−22
−23
2.2
2.4
2.6
2.8
3.0
3.2
3.4
log(wavlength) [microns]
J=10→9
J=9→8
J=8→7
J=7→6
J=6→5
J=5→4
J=4→3
J=3→2
J=2→1
J=1→0

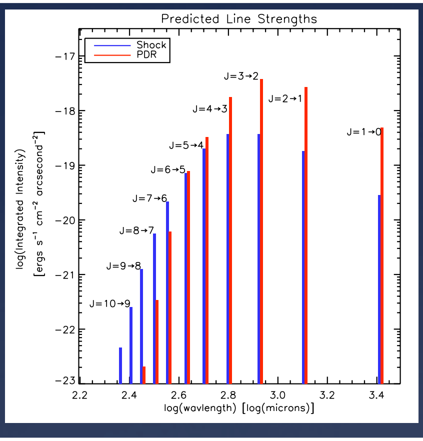
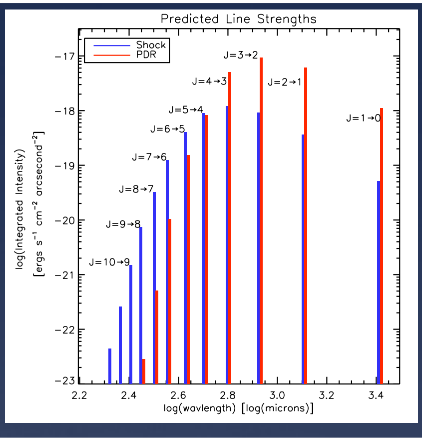
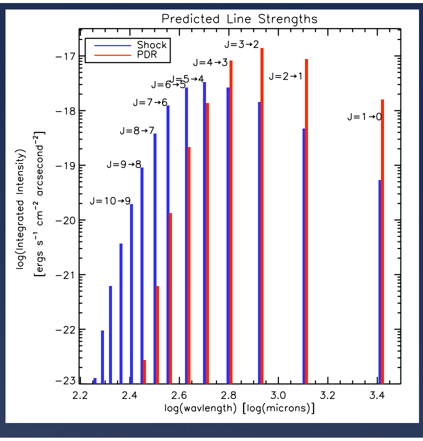
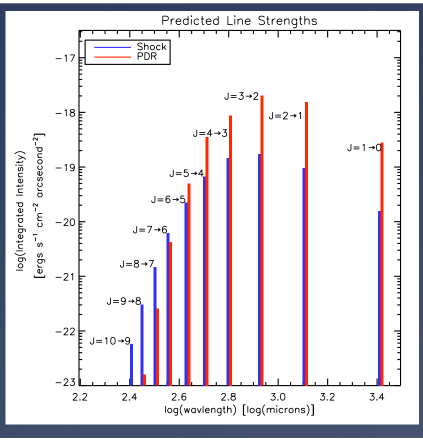
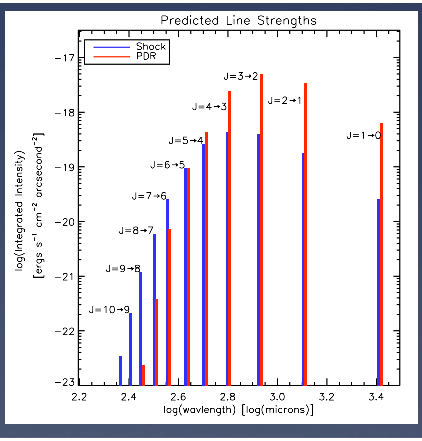
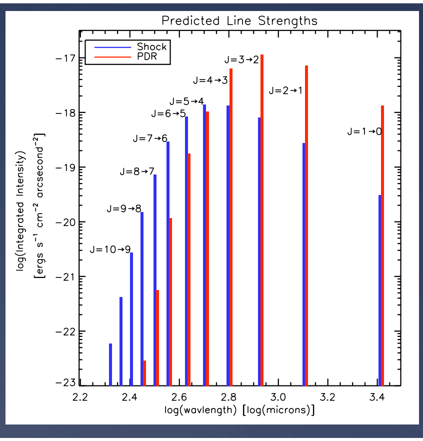
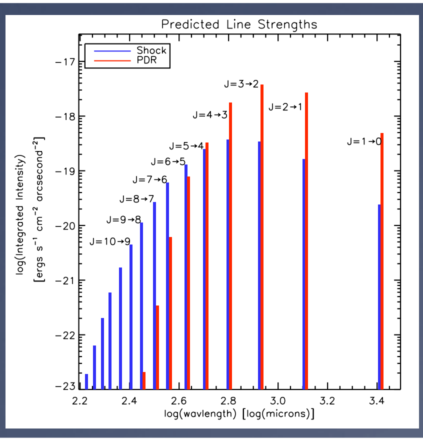
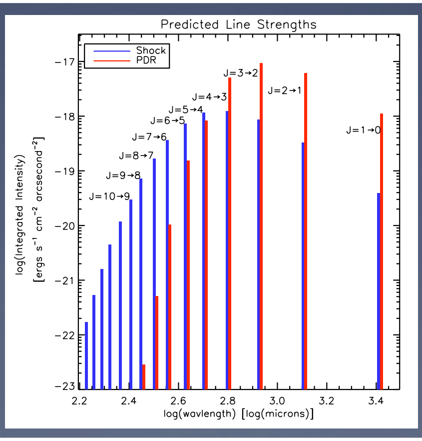
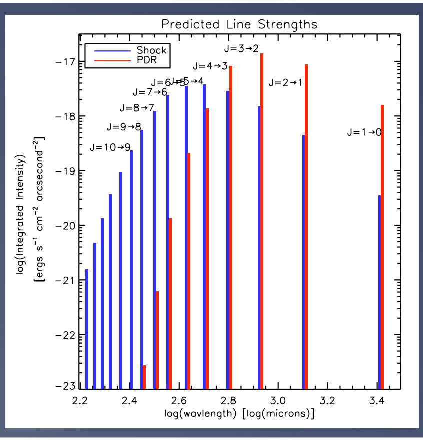
Photodissociation Region (PDR) Model

- PDR model from Kaufman et al. (1999)
- Density of 1000 cm^{-3}
- Interstellar radiation field of 3 Habing
- Microturbulent Doppler line width of 1.5 km / s
- Extends to an A_V of approximately 10


Predicted Line Strengths
Shock
PDR
J=10→9
J=9→8
J=8→7
J=7→6
J=6→5
J=5→4
J=4→3
J=3→2
J=2→1
J=1→0
−17
−18
−19
−20
−21
−22
−23
log(Integrated Intensity)
[ergs s^{-1} cm^{-2} arcsecond^{-2}]
2.2
2.4
2.6
2.8
3.0
3.2
3.4
log(wavlength) [log(microns)]


Predicted Line Strengths
Shock
PDR
J=1→0
J=2→1
J=3→2
J=4→3
J=5→4
J=6→5
J=7→6
J=8→7
J=9→8
J=10→9
2
1
0
−1
−2
−3
−4
−5
2.2
2.4
2.6
2.8
3.0
3.2
3.4
log(Integrated Intensity)
[K km s^{-1}]
log(wavlength) [log(microns)]


ATM 2002 Model (Pardo et al.)
Zeus-2 Bands
273 K
PWV
CCAT 10% 5600 m 150 μm
CCAT 25% 5600 m 400 μm
CCAT 50% 5600 m 700 μm
ALMA 50% 5000 m 1000 μm
CSO 50% 4100 m 2000 μm
Transmission
1
0.5
0
500
5-4
6-5
7-6
8-7
1000
1500
Frequency [GHz]

	$n = 10^{2.5}$ cm^{-3}	$n = 10^{3}$ cm^{-3}	$n = 10^{3.5}$ cm^{-3}
v = 3 km s^{-1} b = 0.3			
v = 2 km s^{-1} b = 0.1			
v = 3 km s^{-1} b = 0.1			

Summary

(see ApJ, submitted May 2011 for more detail)

- Magnetic field compression removes a significant (15-45%) fraction of a shock's energy
- H_2 rotational lines trace shocks with Alfvénic Mach numbers > 15
- CO rotational transitions dissipate the majority of the energy
- Low J lines are dominated by PDR emission
- Mid to high lines trace shock emission!