CO: EXOTIC & NON-STANDARD EXCITATION

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- Preliminaries: overlooked terms in the rate equations
- UV pumping of CO
- Excitation upon formation
- Triplet states of CO & electron-impact
- A digression on OH^+

The usual rate equations for steady-state populations are

$$\frac{dn_i}{dt} = \sum_{j>i} n_j A_{ji} - \sum_{k<i} n_i A_{ik} + \sum_{\ell \neq i} \Big(n_\ell C_{\ell i} - n_i C_{i\ell} \Big) = 0$$

But this ignores source and sink terms as well as coupling to external radiation and it yields relative populations only.

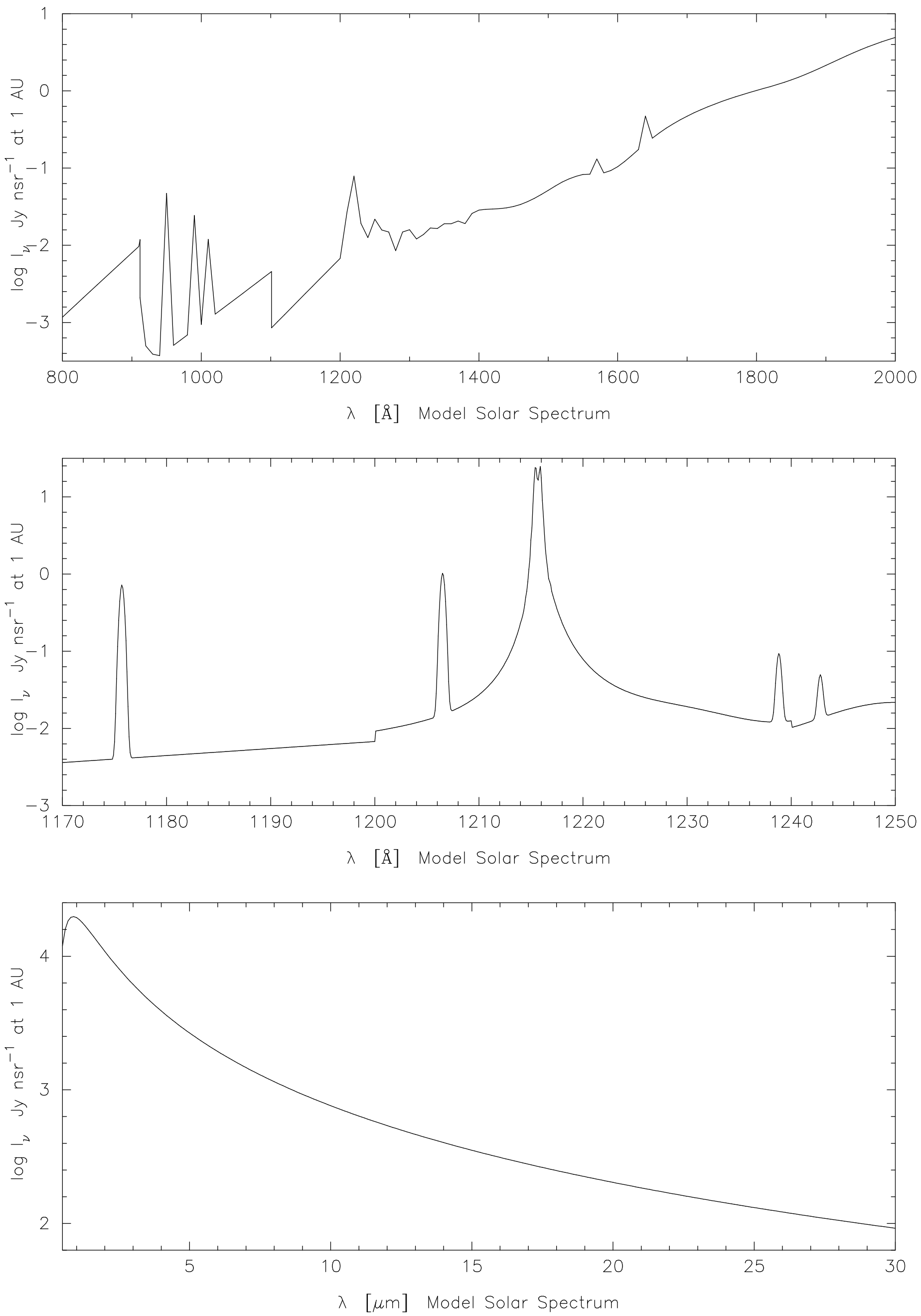
We recommend

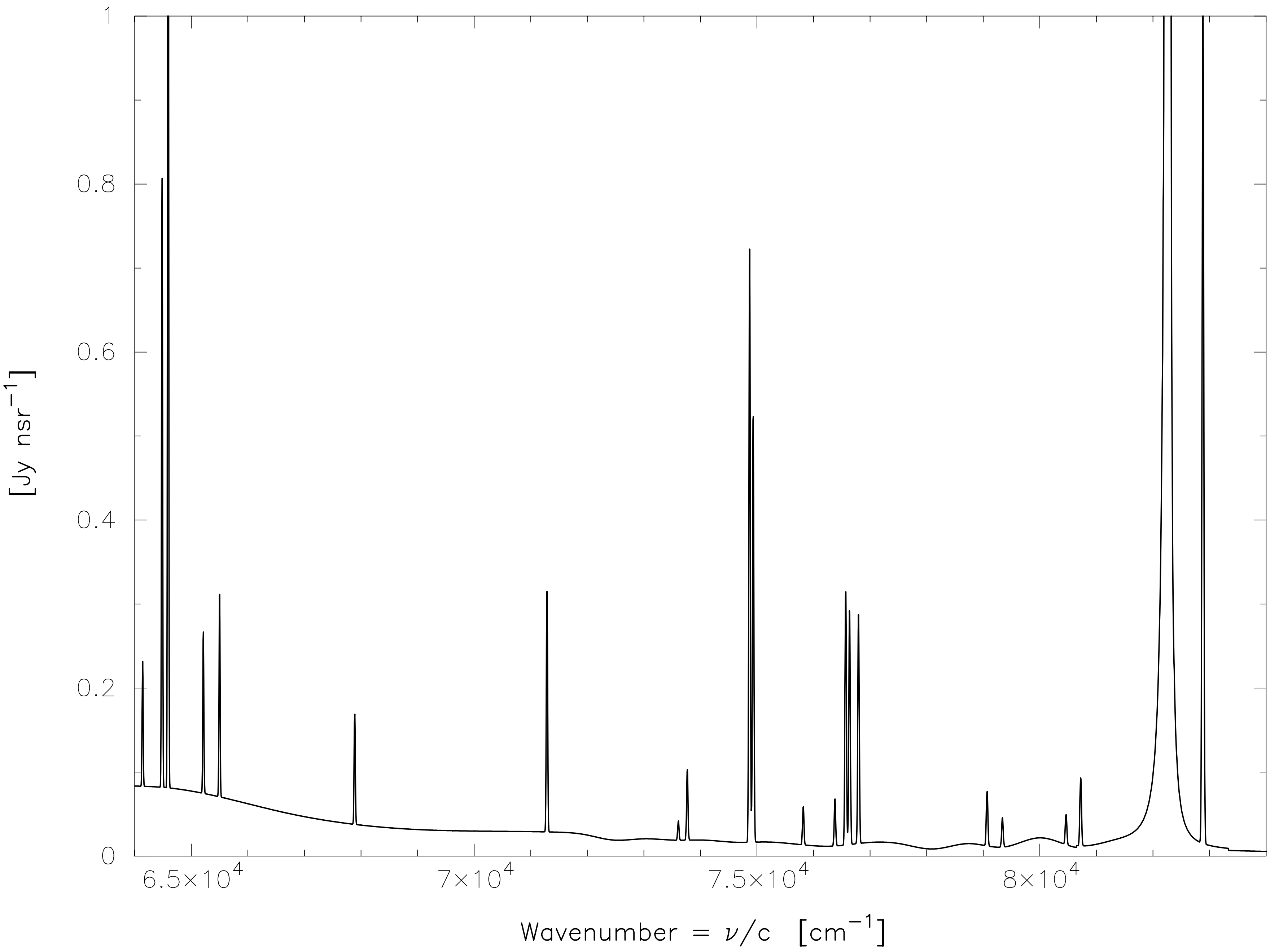
$$\frac{dn_i}{dt} = \sum_{j>i} n_j \Big(A_{ji} + I_\nu B_{ji} \Big) - \sum_{k<i} \Big[n_i \Big(A_{ik} + I_\nu B_{ik} \Big) - n_k I_\nu B_{ki} \Big]$$

$$+ \sum_{\ell \neq i} \Big(n_\ell C_{\ell i} - n_i C_{i\ell} \Big) = F_i(T_{\mathrm{form}}) - n_i D_i$$

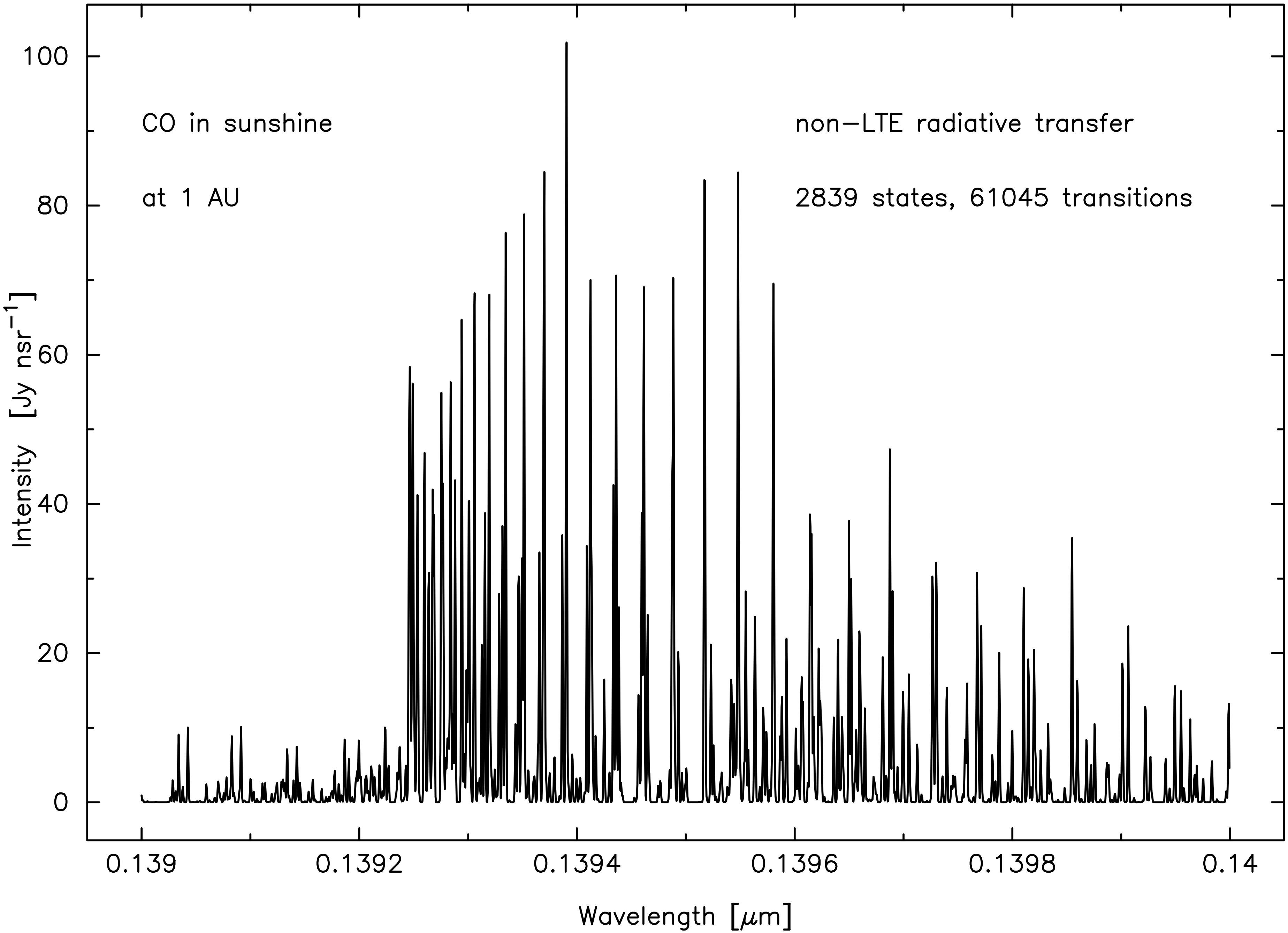
The state-specific formation rate F_i is a model of the formation process (e.g. a Boltzmann distribution at some formation temperature T_{form}). It permits different spin-modifications to be treated together even without reactive interchange processes. For properly chosen F_i and D_i, the solutions are number densities.

Input solar spectrum UV from chromosphere and corona represents an enormous excess over the Teff=5800 K photosphere

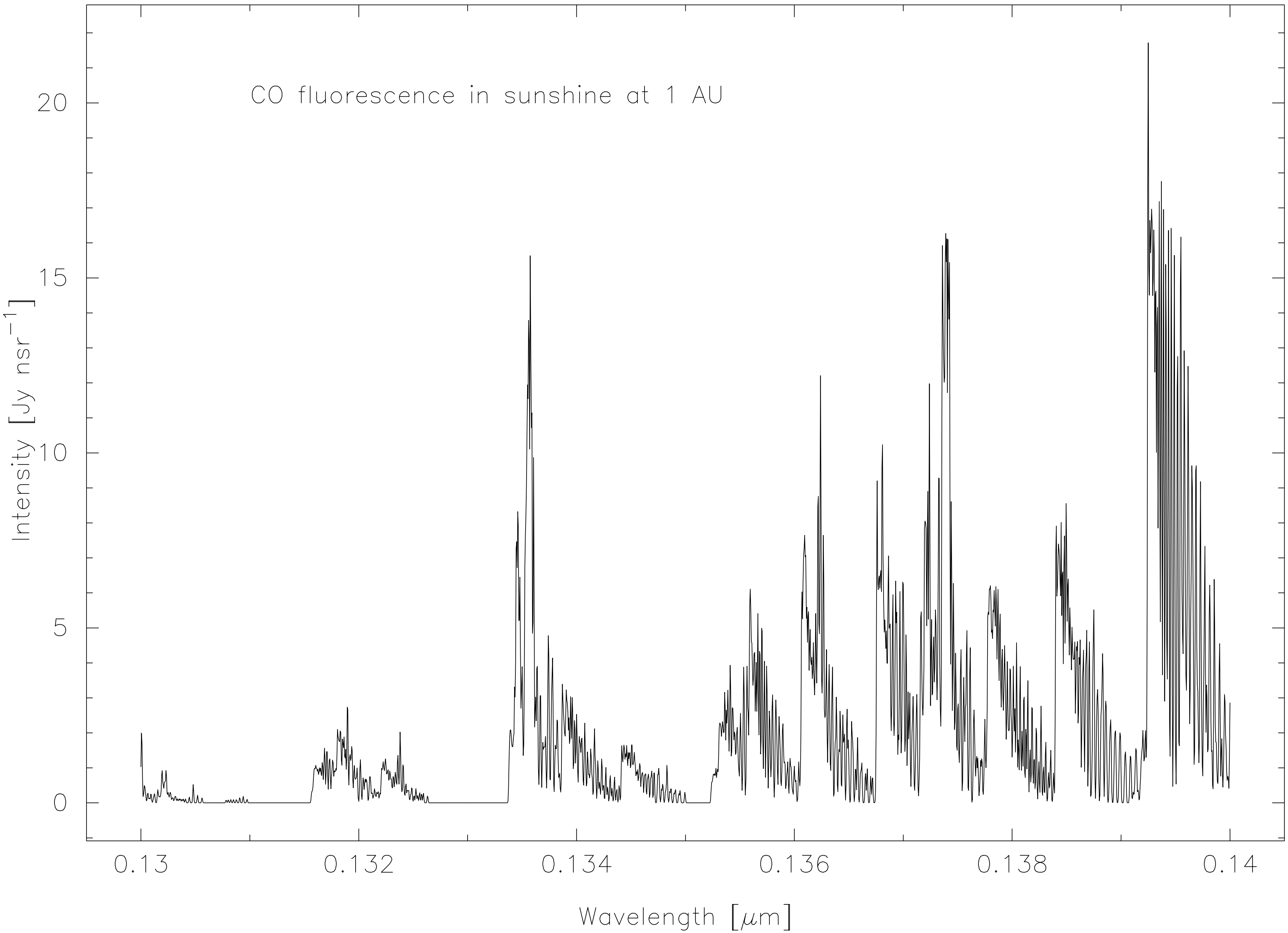



1
0.8
0.6
0.4
0.2
0
[Jy nsr^{-1}]
6.5×10^4
7×10^4
7.5×10^4
8×10^4
Wavenumber = ν/c [cm^{-1}]

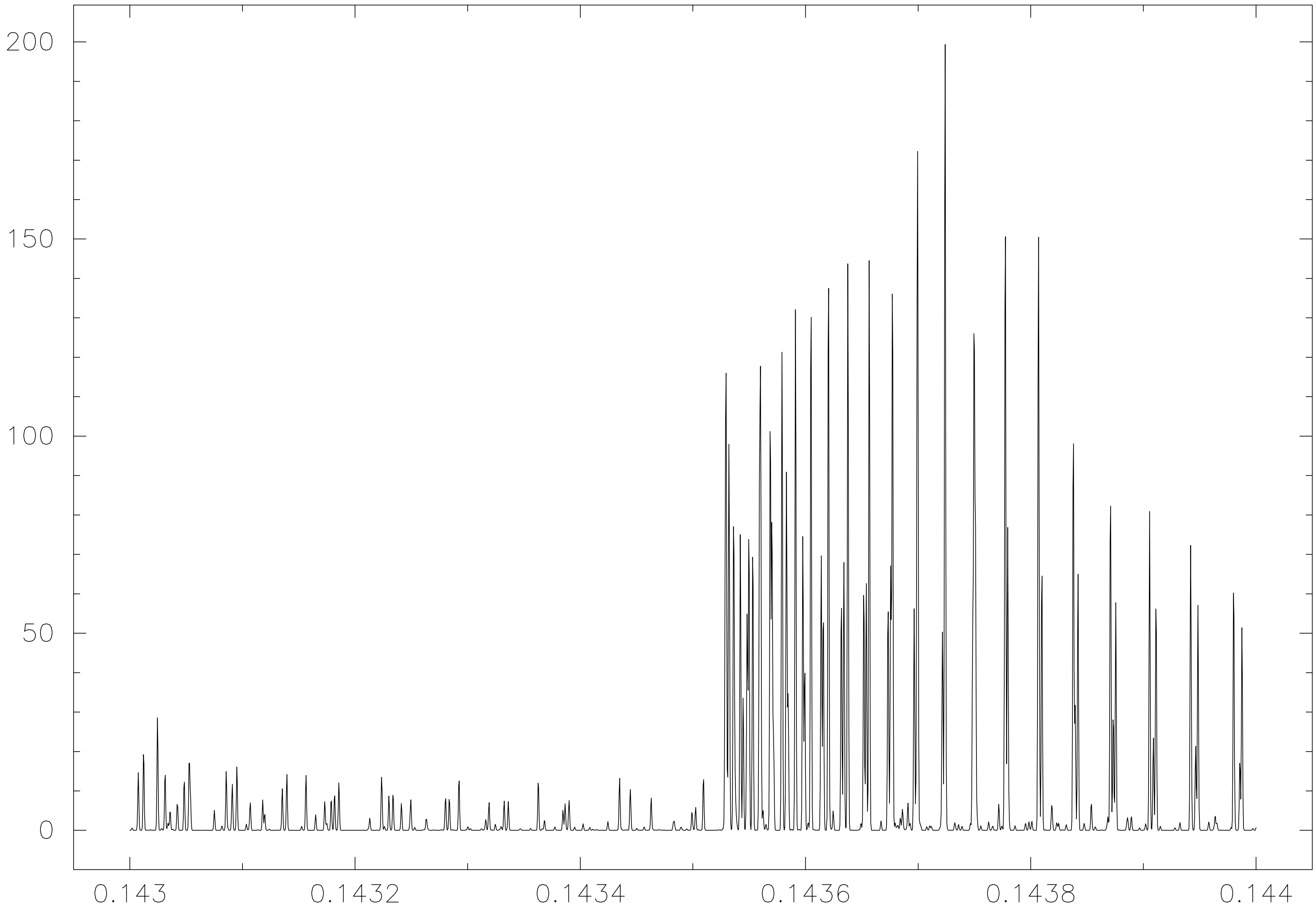
Example: UV-pumped CO in sunlight

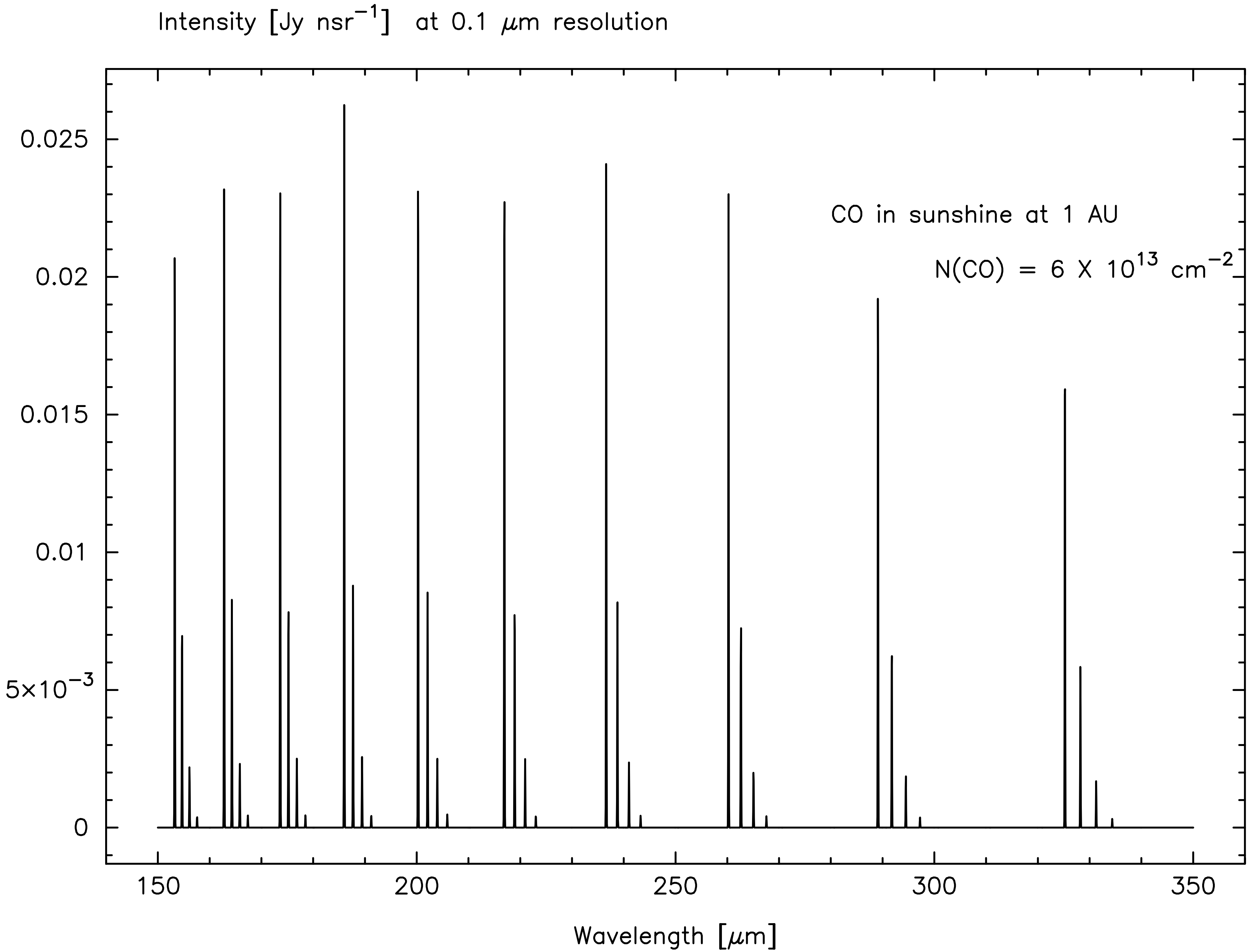


J.H. Black & J. L. Fox (in preparation)



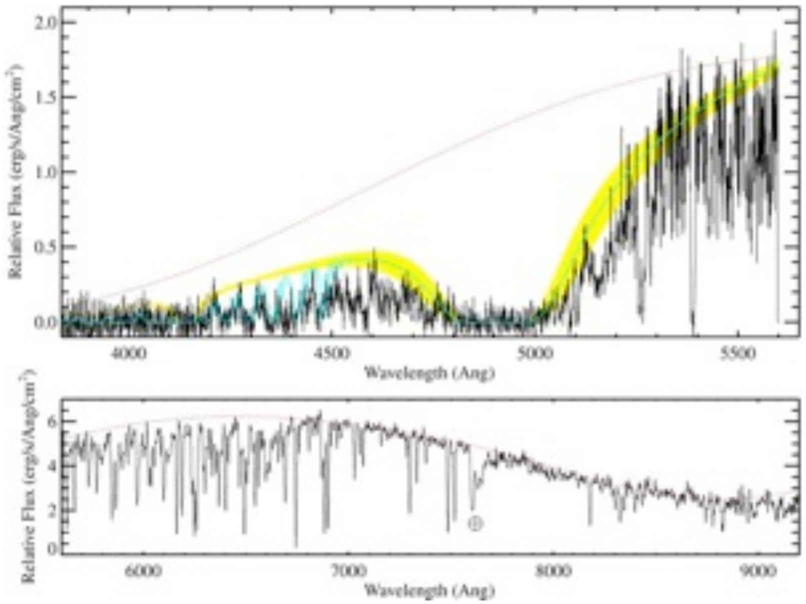
CO fluorescence in sunshine at 1 AU
Intensity [Jy nsr^{-1}]
Wavelength [μm]
0.13
0.132
0.134
0.136
0.138
0.14
0
5
10
15
20

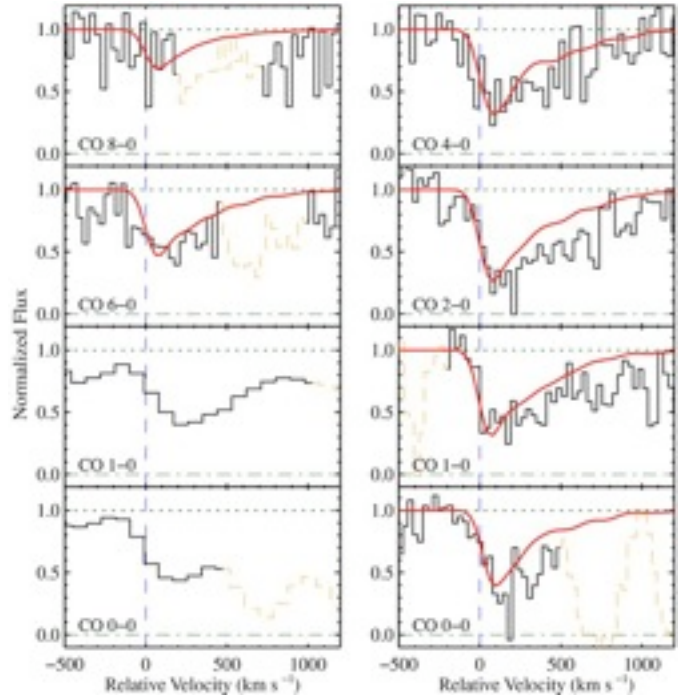

200
150
100
50
0
0.143
0.1432
0.1434
0.1436
0.1438
0.144



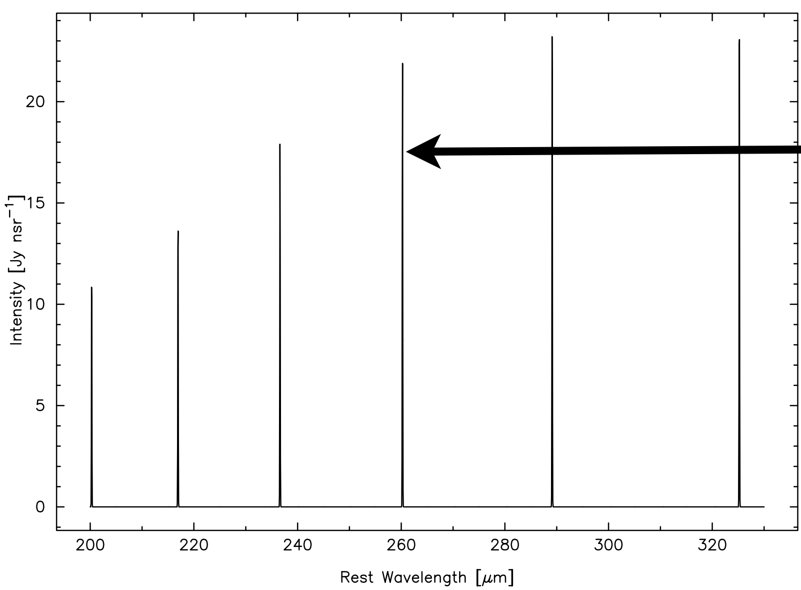
Intensity [Jy nsr^{-1}] at 0.1 μm resolution
CO in sunshine at 1 AU
N(CO) = 6 X 10^{13} cm^{-2}
0.025
0.02
0.015
0.01
5×10^{-3}
0
150
200
250
300
350
Wavelength [μm]

GRB080607: H_2 and CO at z=3.0363

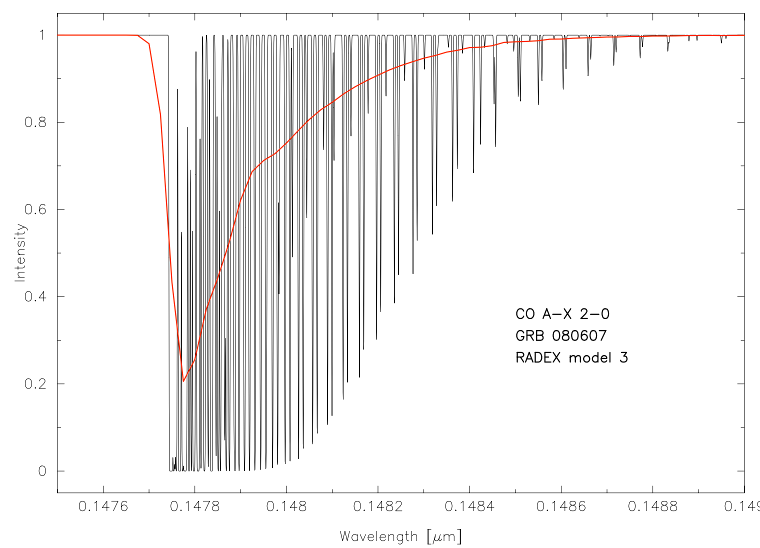




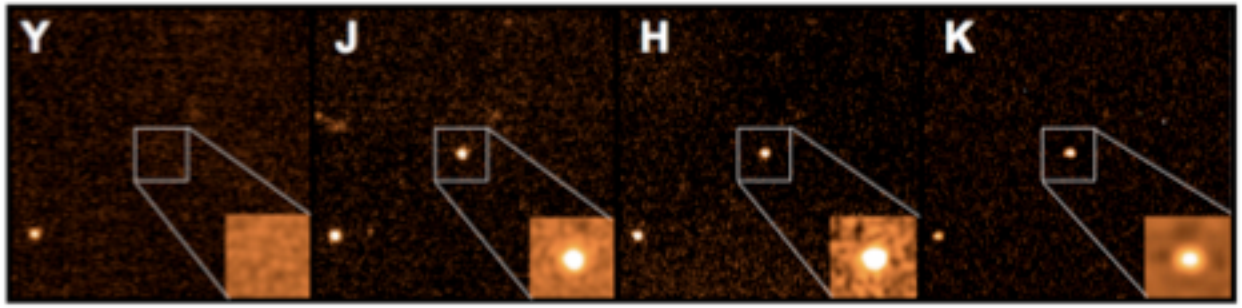
Prochaska et al. (2009, ApJ, 691, L27), Sheffer et al. (2009, ApJ, 701, L63) show that H2 is pumped by the UV afterglow ↑
Black (2009, in prep.) predicts the UV pumping in CO, which produces submm-wave emission, too ↓



CO J=12-11
1.38 THz (rest)
red-shifted to
342.4 GHz
at z=3.0363



Afterglows of γ-ray Bursts at High Redshift



UKIRT discovery images from Tanvir et al. astro-ph:0906.1577

GRB090423 was the most distant known source in the Universe at z=8.26

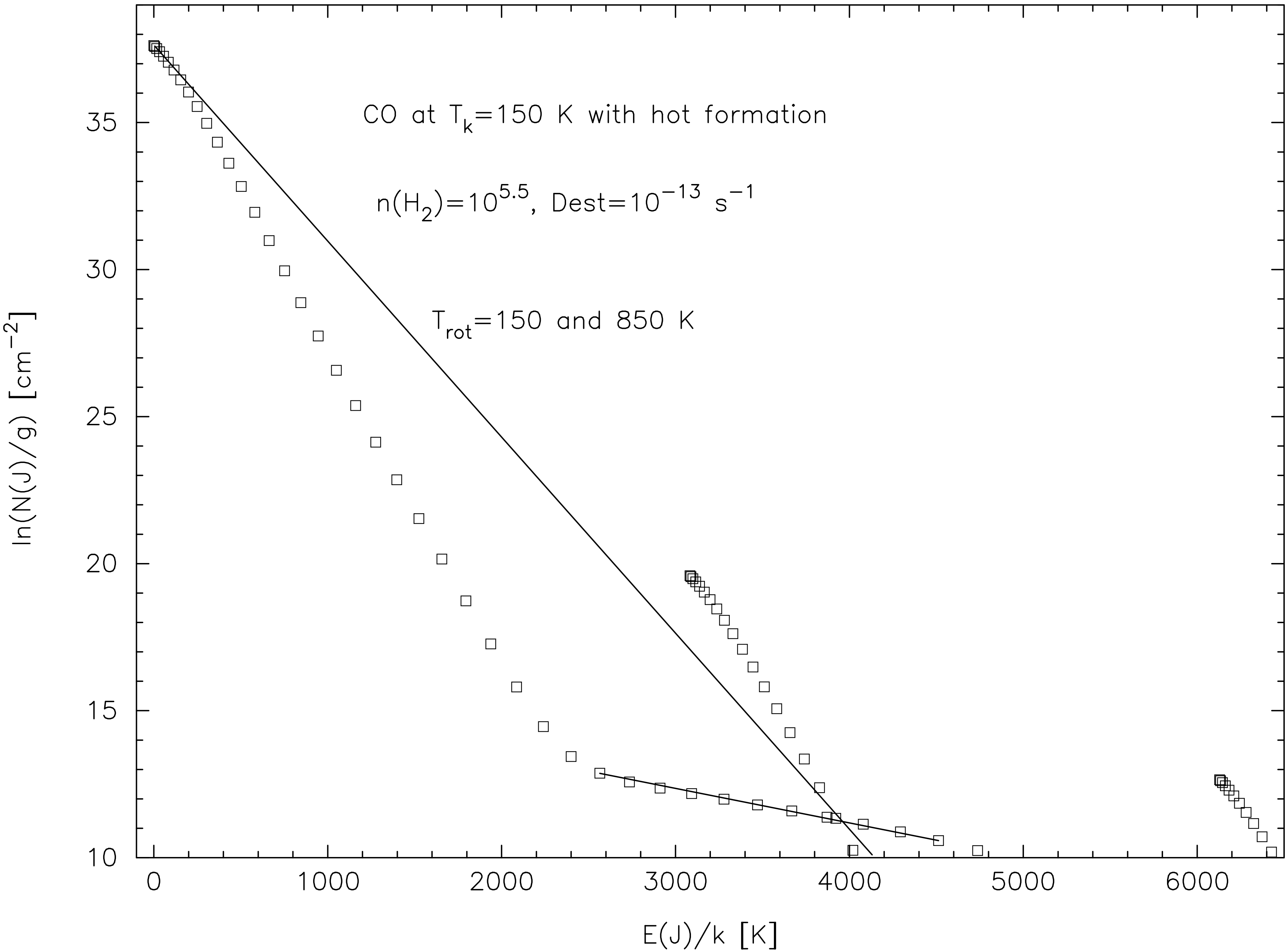
mm/submm-wave afterglow?

Castro-Tirado et al. report a λ=3 mm source at the burst position with flux density 0.2 mJy (GCN Circular 9273, 09-04-28)

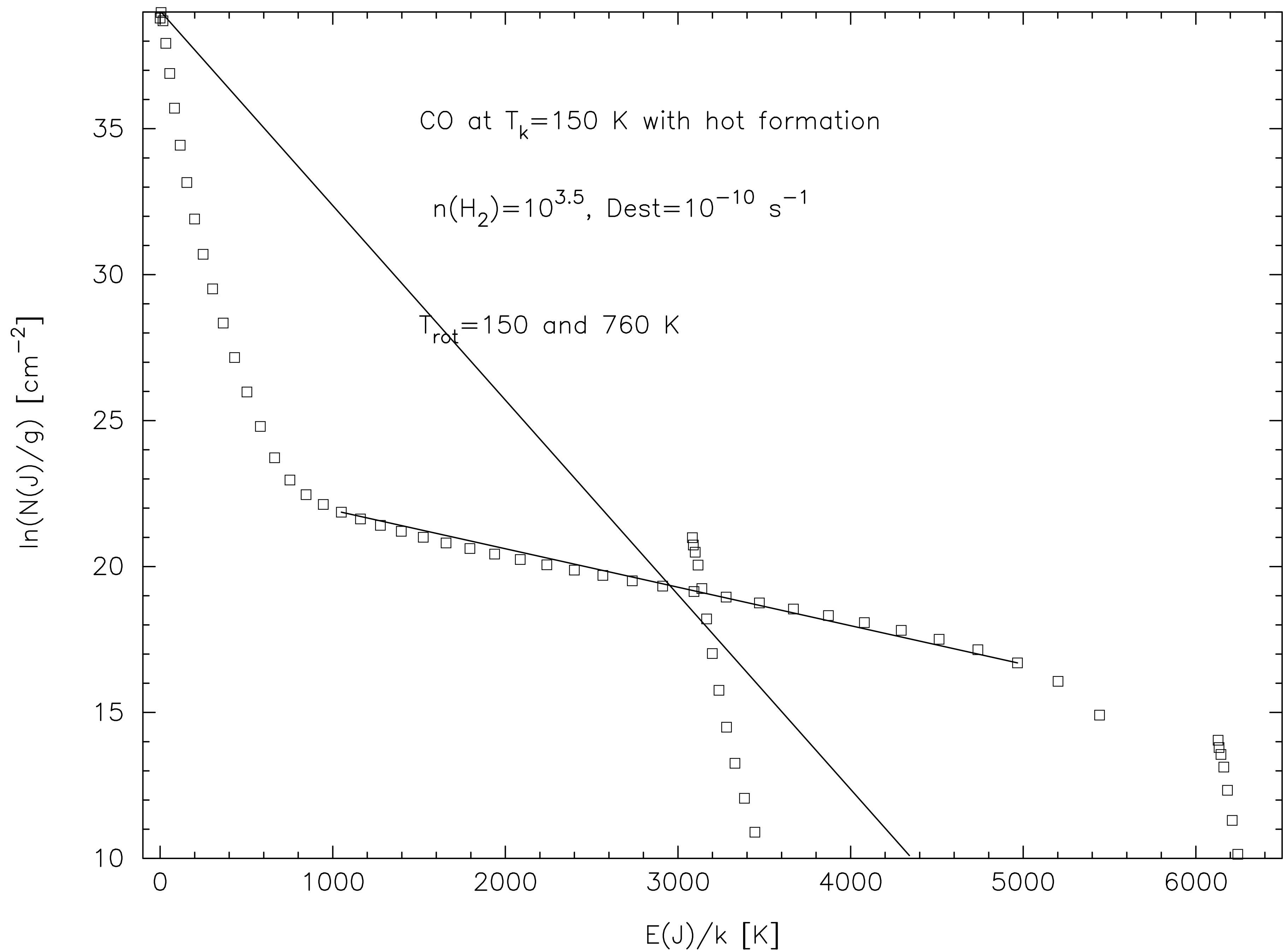
consistent with Bock et al. upper limit of 0.7 mJy at CARMA

⇒Prospects for ALMA to probe high-z galaxies

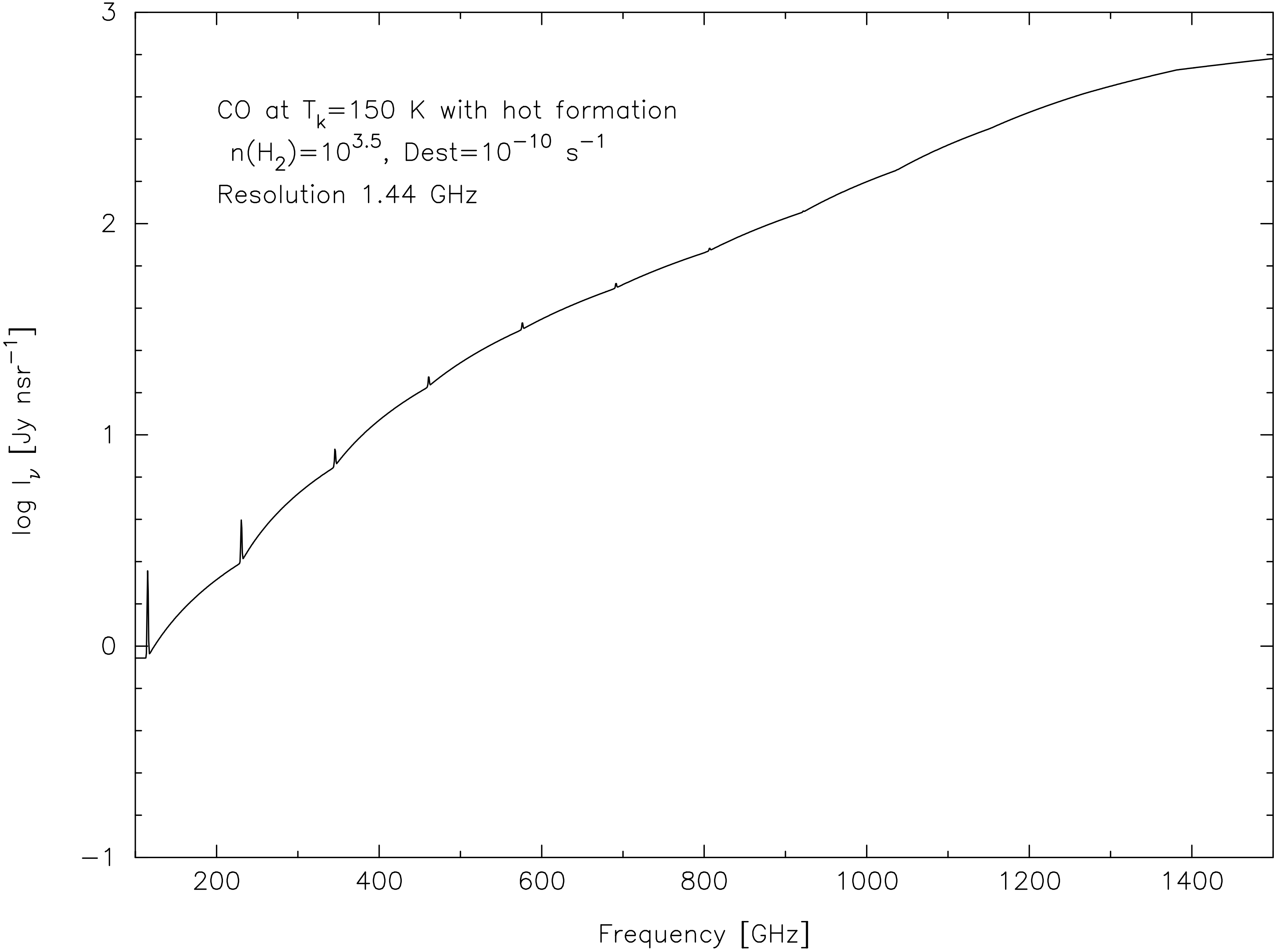
- CO can be formed with considerable internal energy
- Example: $HCO^+ + e^- \rightarrow H + CO(v,J) + 7.5$ eV
- Set formation rate according to HCO^+ and e^- abundances
- In PDR/XDR this could be $F=4\times10^{-19}\, n^2$ [$cm^{-3}\, s^{-1}$] or higher
- Balance with a destruction rate that gives the needed CO abundance or column density
- Apply RADEX in all-singing, all-dancing mode



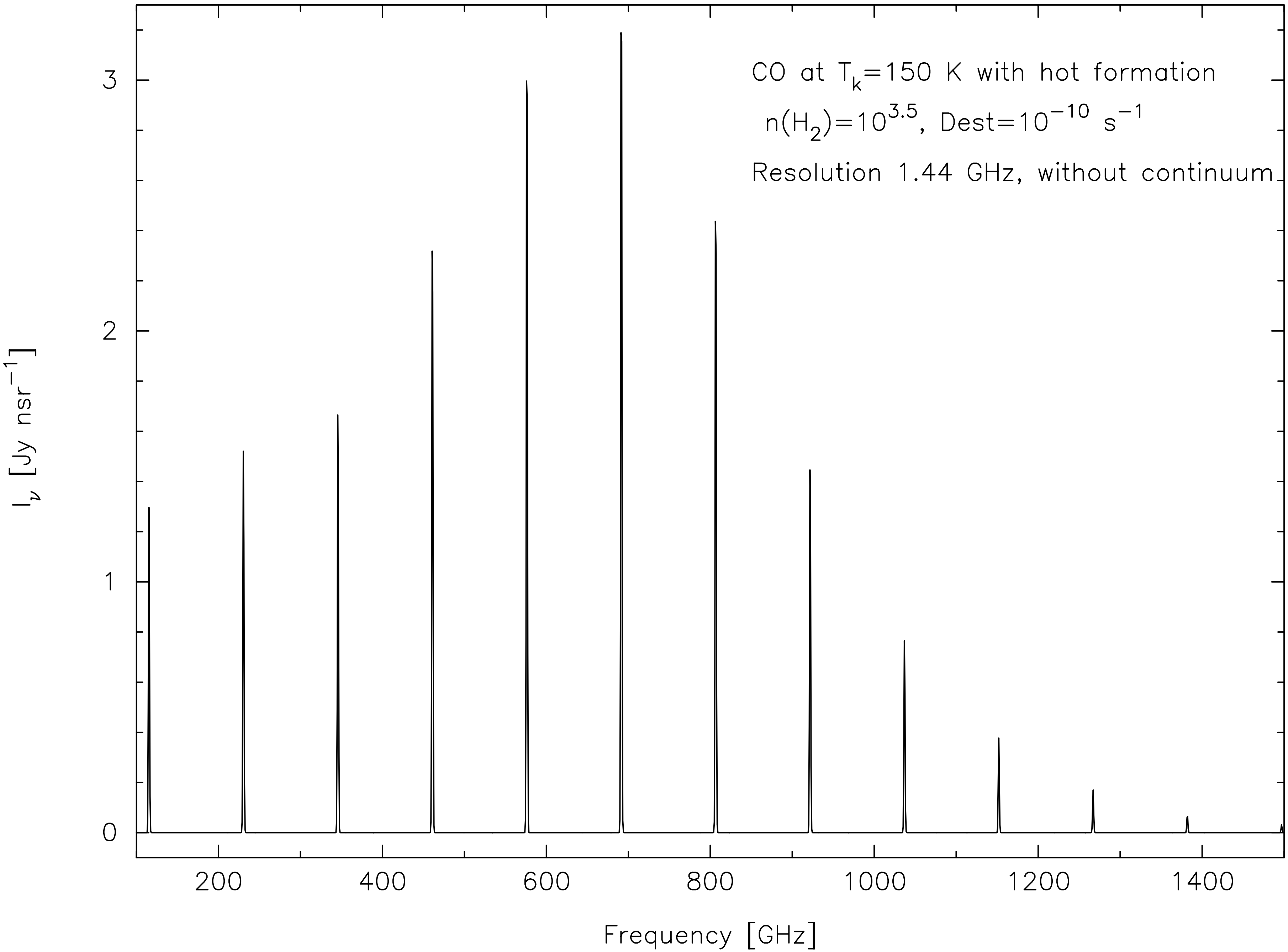
CO at T_k=150 K with hot formation
$n(H_2)=10^{5.5}$, Dest=10^{-13} s^{-1}
T_{rot}=150 and 850 K
ln(N(J)/g) [cm^{-2}]
E(J)/k [K]
35
30
25
20
15
10
0
1000
2000
3000
4000
5000
6000



CO at T$_k$=150 K with hot formation
n(H$_2$)=10$^{3.5}$, Dest=10^{-10} s^{-1}
T$_{rot}$=150 and 760 K
ln(N(J)/g) [cm^{-2}]
E(J)/k [K]
35
30
25
20
15
10
0
1000
2000
3000
4000
5000
6000

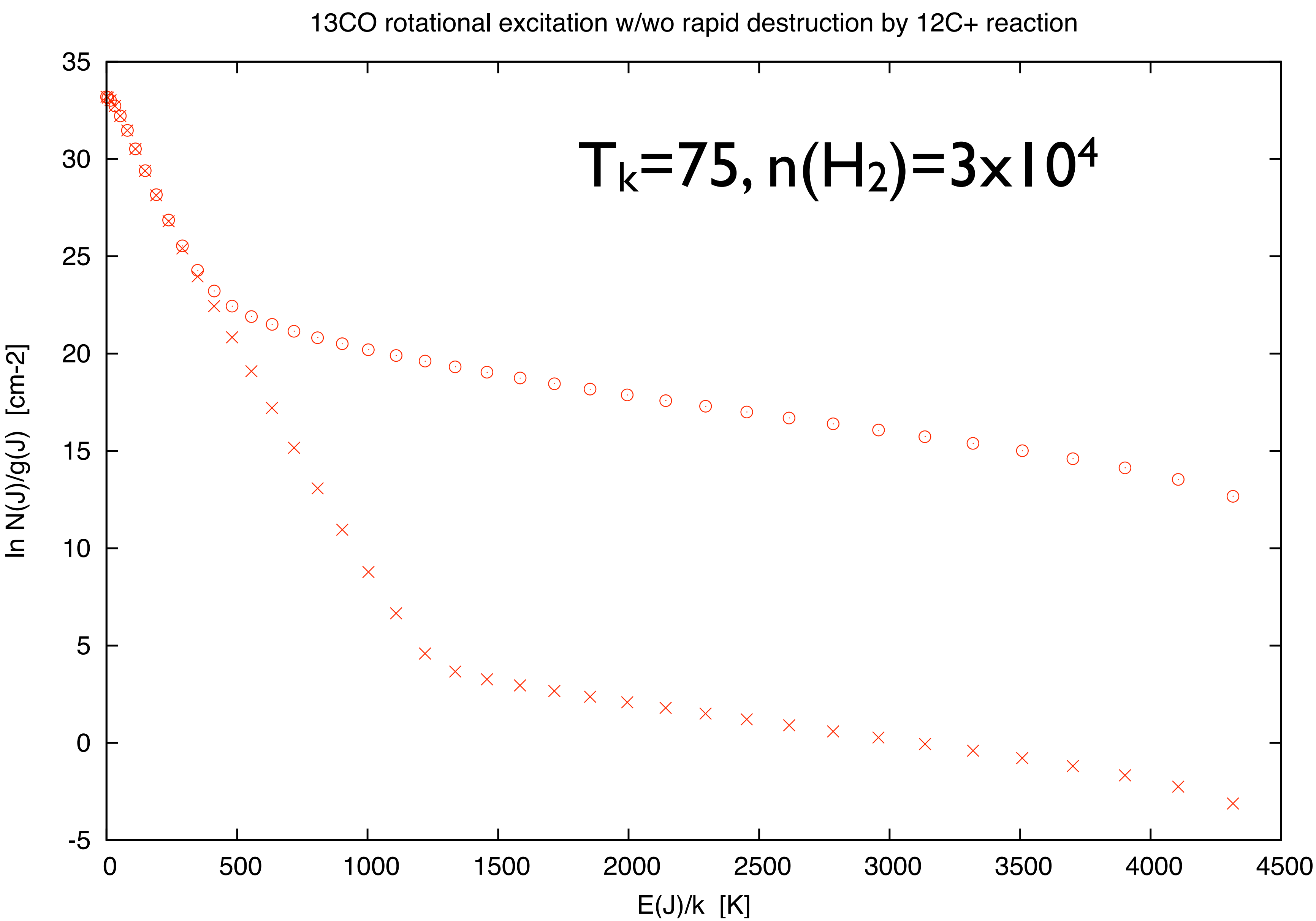


CO at T_k=150 K with hot formation
$n(H_2)=10^{3.5}$, Dest=10^{-10} s^{-1}
Resolution 1.44 GHz
log I_ν [Jy nsr^{-1}]
Frequency [GHz]
3
2
1
0
−1
200
400
600
800
1000
1200
1400



CO at T_k=150 K with hot formation
$n(H_2)=10^{3.5}$, Dest=10^{-10} s^{-1}
Resolution 1.44 GHz, without continuum
I_ν [Jy nsr^{-1}]
Frequency [GHz]
0
1
2
3
200
400
600
800
1000
1200
1400

Formation/destruction may be important in common molecules if the rates are fast enough.
For example, $^{13}CO + ^{12}C^+ \rightarrow ^{12}CO + ^{13}C^+$ in PDR can mimic a high-temperature component.



- Recent evidence from UV spectra of T Tau disks that CO is excited both by UV fluorescence and e-impact (France et al. 2011)

- Hot electrons are expected in XDR and in magnetospheres of Jupiter-like planets

- Electron collisions are not directly important in rotational excitation of CO (small dipole moment)

- Electron collisions can excite triplet electronic states

S. G. TILFORD AND J. D. SIMMONS

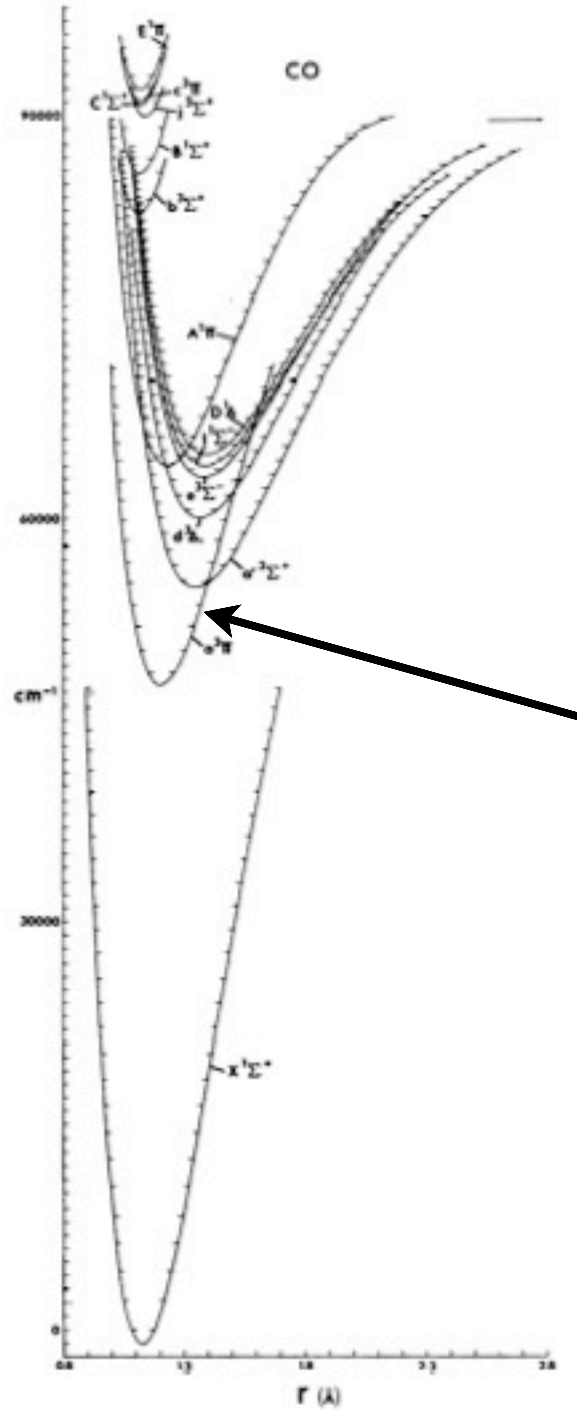


FIGURE 3. Potential energy curves for the observed states of CO below 11.77 eV.

The arrow indicates the dissociation energy of CO. The dash

$a^3\Pi$ is the upper state of the
a-X Cameron system
with (0,0) band near 200 nm
$a^3\Pi$ has a well measured
rotational spectrum;
e.g. v=0, Ω=0 J=1-0 is
a Λ-doublet at 92.5, 92.9 GHz

CO triplets can be excited dissociative recombination, e.g.

$CO_2^+ + e^- \rightarrow CO(d^3\Delta)$

there is a yield of 0.29 for $CO_2^+ + e^- \rightarrow CO(a\text{-}X)$

$HCO^+ + e \rightarrow CO(X) + H + 7.31$ eV

$HCO^+ + e \rightarrow CO(a^3\Pi) + 1.30$ eV [0.23 yield]

$HCO^+ + e \rightarrow CO(a'\,^3\Sigma^+) + 0.44$ eV

and $HOC^+ + e$ has even more accessible states in product CO

(R. Johnsen et al. 2009)

J-dependence of $a^3\Pi$ lifetimes suggests population inversions might easily occur

CO triplet bands show up in the UV spectrum of HD 44179 (Red Rectangle)

while this is an AGB star in a binary system, the source of UV radiation has been identified as the hot, inner region of an accretion disk

(Witt et al 2009)

in comets, CO(a-X) comes from CO_2 photodissociation and e-impact

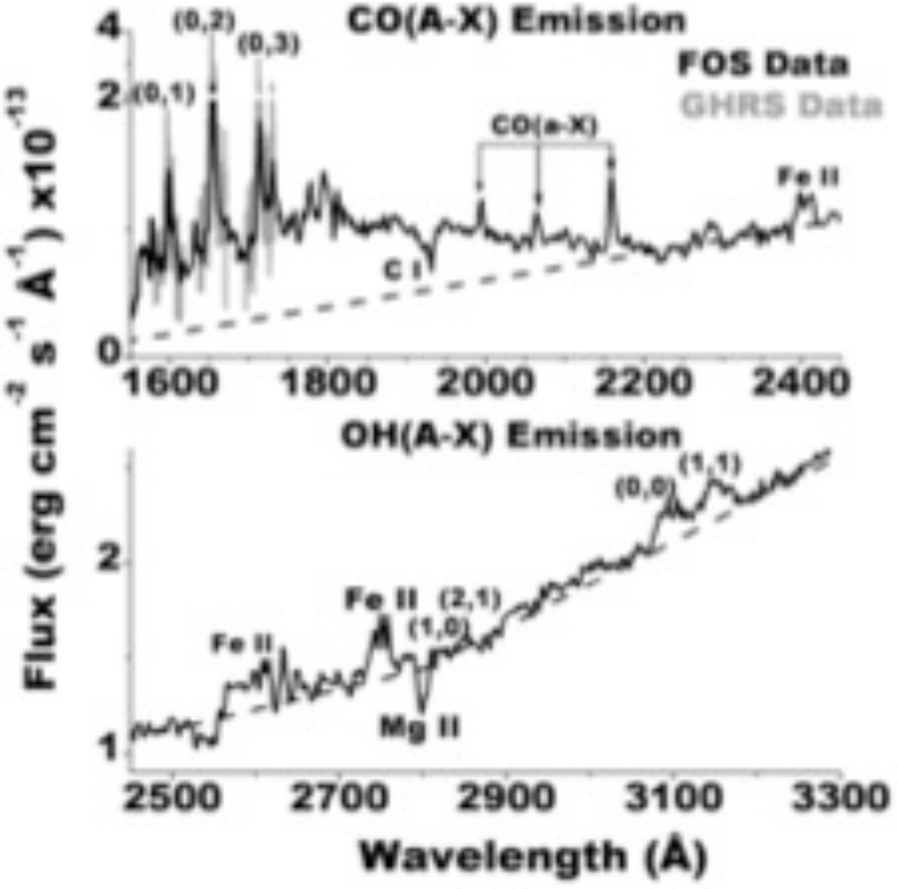


FIG. 3.—*Top*: FOS and GHRS data are compared in the CO($A-X$) emission region. *Bottom*: FOS data in the OH($A-X$) emission region. Also shown is the estimated underlying continuum for the FOS data.

CO Cameron bands in the Red Rectangle

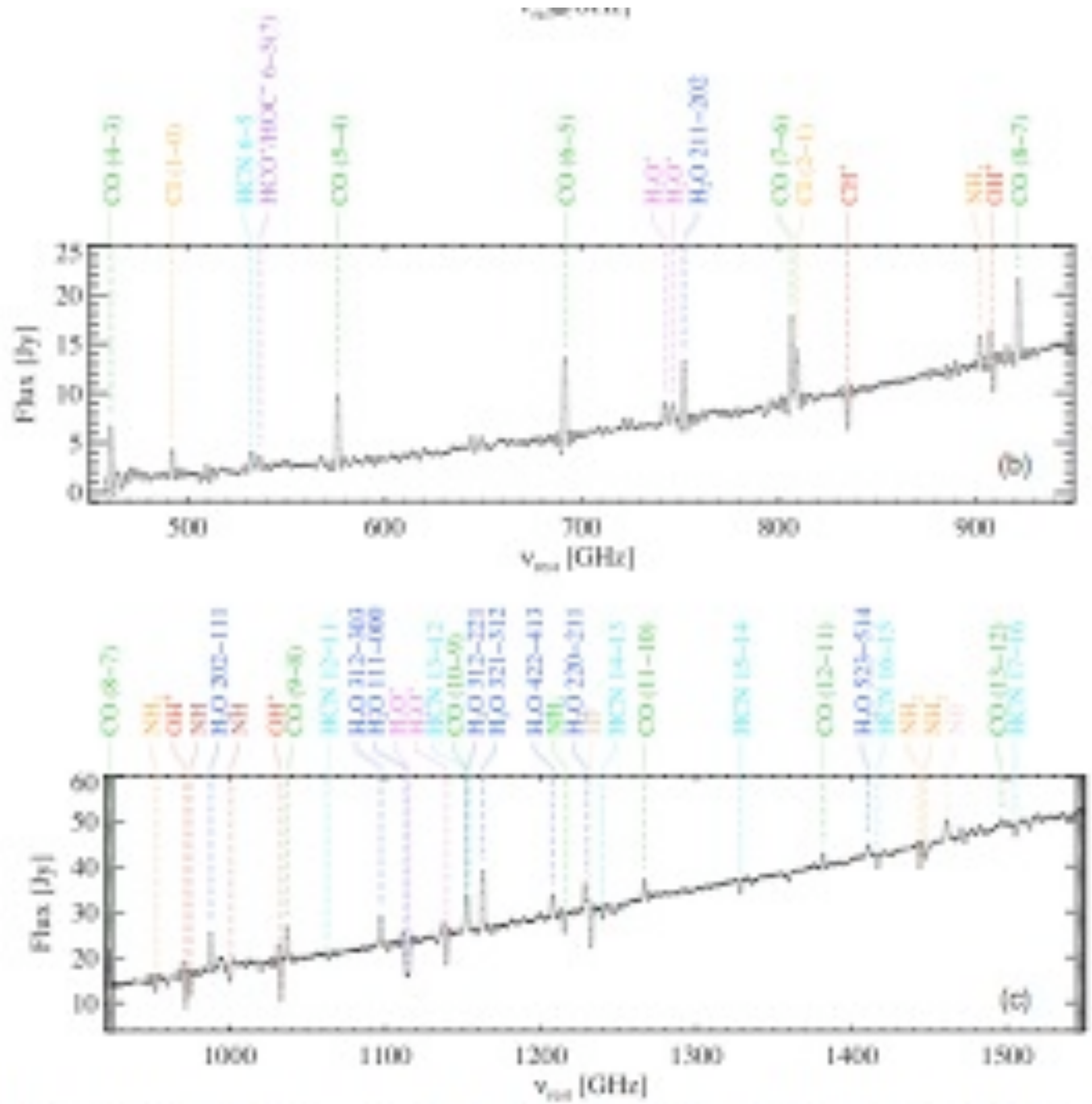


Figure 1. *Herschel* SPIRE-FTS spectrum of Arp 220. The spectrum shows the FIR continuum between 190 and 670 μm in (a). Red solid points in (a) are the continuum measurements from the SPIRE photometer and the dotted curves show the photometer bandpasses with arbitrary normalization. Line identifications are shown for several molecular and atomic species in (b) and (c) with like colors for like species.

(A color version of this figure is available in the online journal.)

OH^+ absorption/emission in Arp 220
Rangwala et al. (2011)

P. P. van der Werf et al.: Seperation of AGN and starburst in Mrk 231

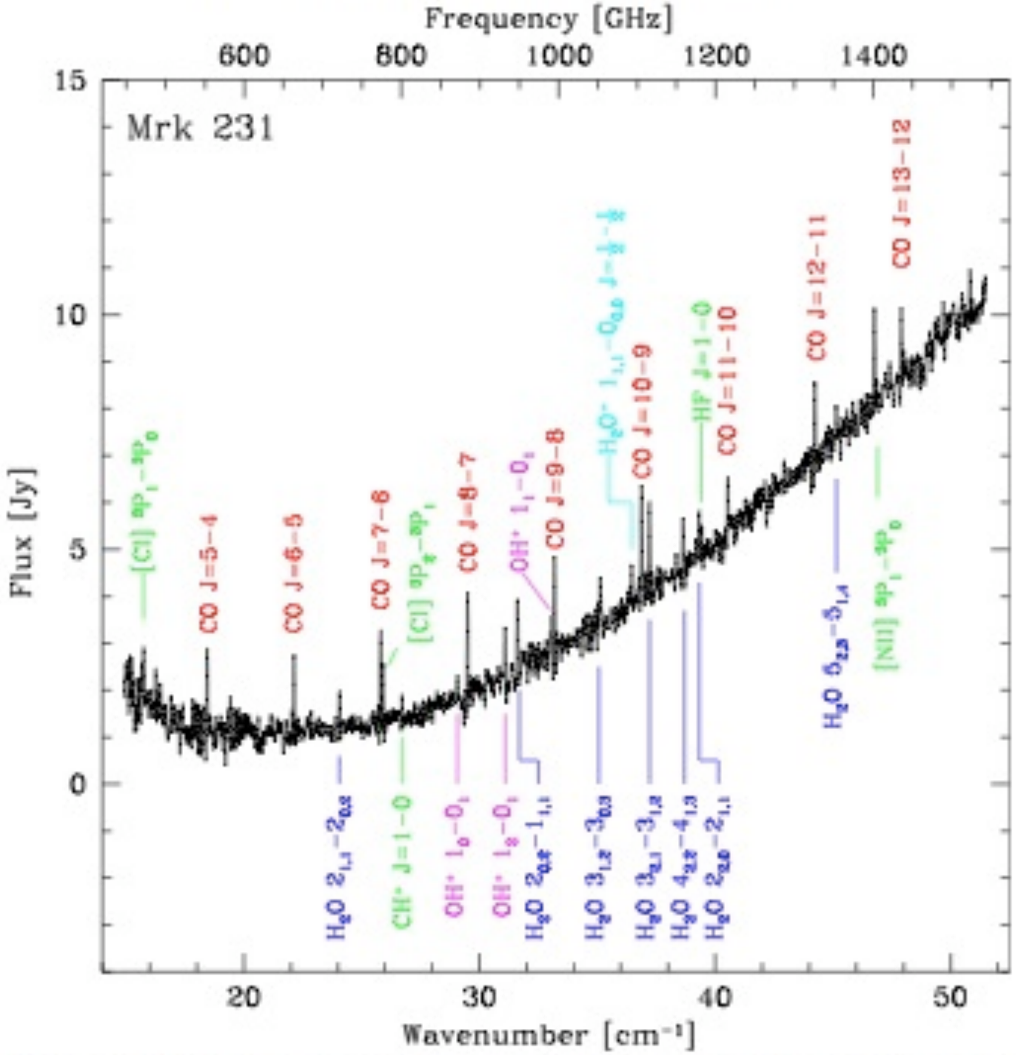
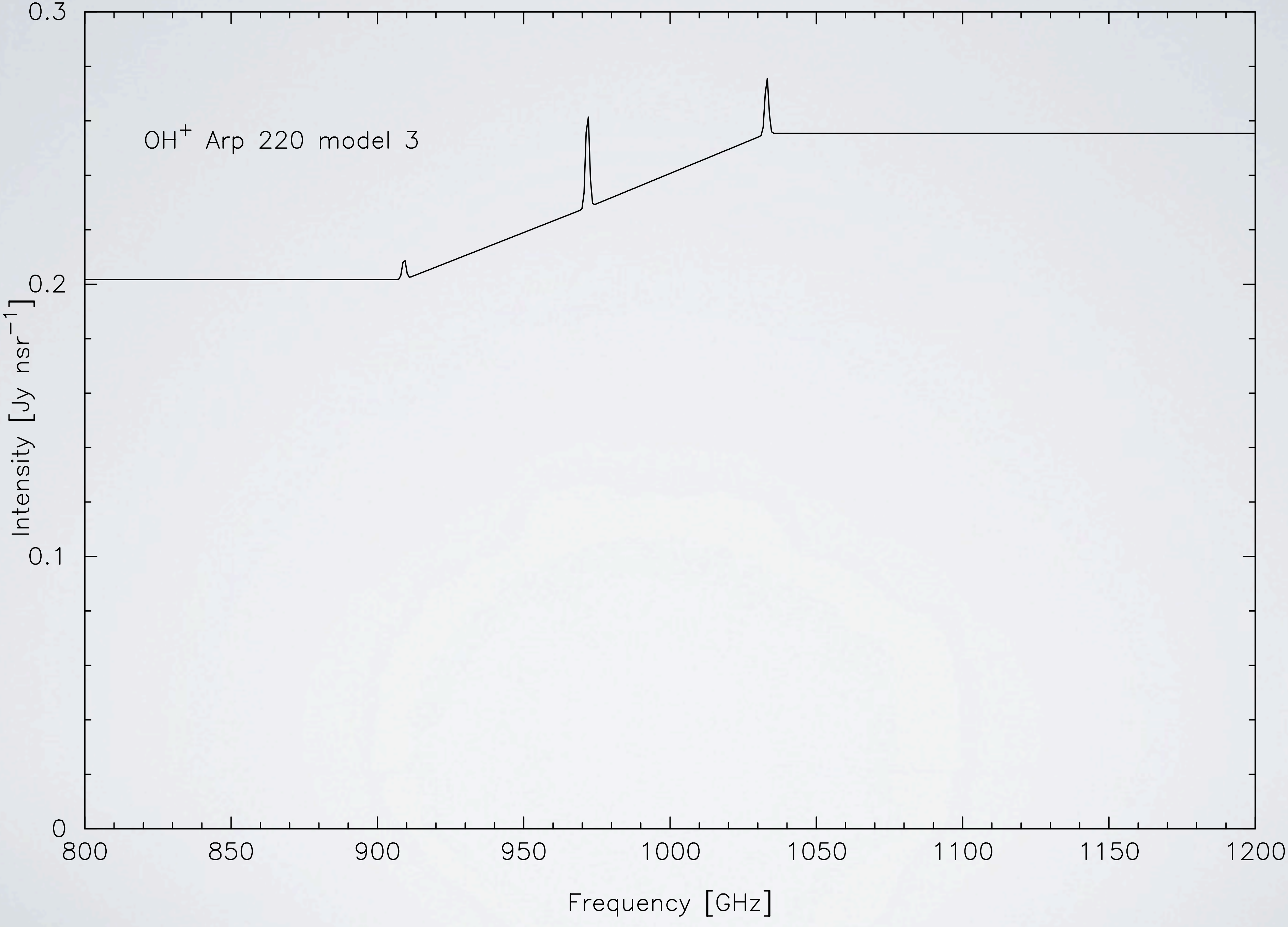


Fig. 1. SPIRE FTS spectrum of Mrk 231. Line identifications are given in red for CO lines, in blue for H_2O, in magenta for OH^+, in cyan for H_2O^+, and in green for the remaining lines.

OH^+ in Mrk 231 (van der Werf et al. 2010)

How does OH^+ work?

- 909, 971, 1033 GHz lines: $A = 0.02\ s^{-1}$
- Destruction: by $OH^+ + e^- \rightarrow O + H$, $k = 0.4\times10^{-7}\ cm^3\ s^{-1}$ at T=300 and by $OH^+ + H_2 \rightarrow H_2O^+ + H$, $k = 1.0\times10^{-9}\ cm^3\ s^{-1}$
- Source: $H_3^+ + O \rightarrow OH^+ + H_2$ exoergic by 5200 K
- At $n(H_2) = 10^{5.5}\ cm^{-3}$, $Dest = 3\times10^{-4}\ s^{-1}$, faster than collisional excitation for $n(e) < 400\ cm^{-3}$
- Far-IR pumping at 950 GHz ~ Dest where $T_{rad} = 11$ K ($I = 20$ Jy nsr^{-1})
- SUMMARY: OH+ may naturally appear in emission where electron density is high enough (as in XDR), but the destruction rate must be included explicitly in rate equations. Emission/absorption: dilution of continuum -- relative sizes of central source & molecular gas


OH$^+$ Arp 220 model 3
Intensity [Jy nsr^{-1}]
Frequency [GHz]
0
0.1
0.2
0.3
800
850
900
950
1000
1050
1100
1150
1200