Detection of Infrared Fluorescence of Carbon Dioxide in R Leonis with SOFIA/EXES

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Fonfría et al., 2020, *A&A*, 643, L15

We report on the detection of hot CO_2 in the O-rich AGB star R Leo based on high spectral resolution observations in the range $12.8-14.3$ μm carried out with the Echelon-cross-Echelle Spectrograph (EXES) mounted on the Stratospheric Observatory for Infrared Astronomy (SOFIA). We have found $\simeq 240$ CO_2 emission lines in several vibrational bands. These detections were possible thanks to a favorable Doppler shift that allowed us to avoid contamination by telluric CO_2 features. The highest excitation lines involve levels at an energy of $\simeq 7000$ K. The detected lines are narrow (average deconvolved width $\simeq 2.5$ km s^{-1}) and weak ($\lesssim 10\%$ the continuum). A ro-vibrational diagram shows three different populations, warm, hot, and very hot, with rotational temperatures of $\simeq 550$, 1150, and 1600 K, respectively. We derive a lower limit for the column density of $\simeq 2.2\times10^{16}$ cm^{-2}. Further calculations based on a model of the R Leo envelope suggest that the total column density can be as large as 7×10^{17} cm^{-2} and the abundance with respect to H_2 $\simeq 2.5\times10^{-5}$. The detected lines are probably formed due to de-excitation of CO_2 molecules from high energy vibrational states, which are essentially populated by the strong R Leo continuum at 2.7 and 4.2 μm.

Observations

Observations were carried out with **SOFIA/EXES** on 01 Nov 2018 (UT) in the **High–Low** mode while SOFIA flew at an altitude of **13.1 km**. The slit length for both settings was $\simeq 2''.0$ long and $2''.4$ wide. All EXES data were reduced using the Redux pipeline (Clarke et al. 2015). The median spectral resolving power, $\mathbf{R}=\lambda/\Delta\lambda\simeq \mathbf{70,000}$ (determined from telluric ozone lines). The resulting **spectral resolution** is $\simeq$ **4.3** km s^{-1}.

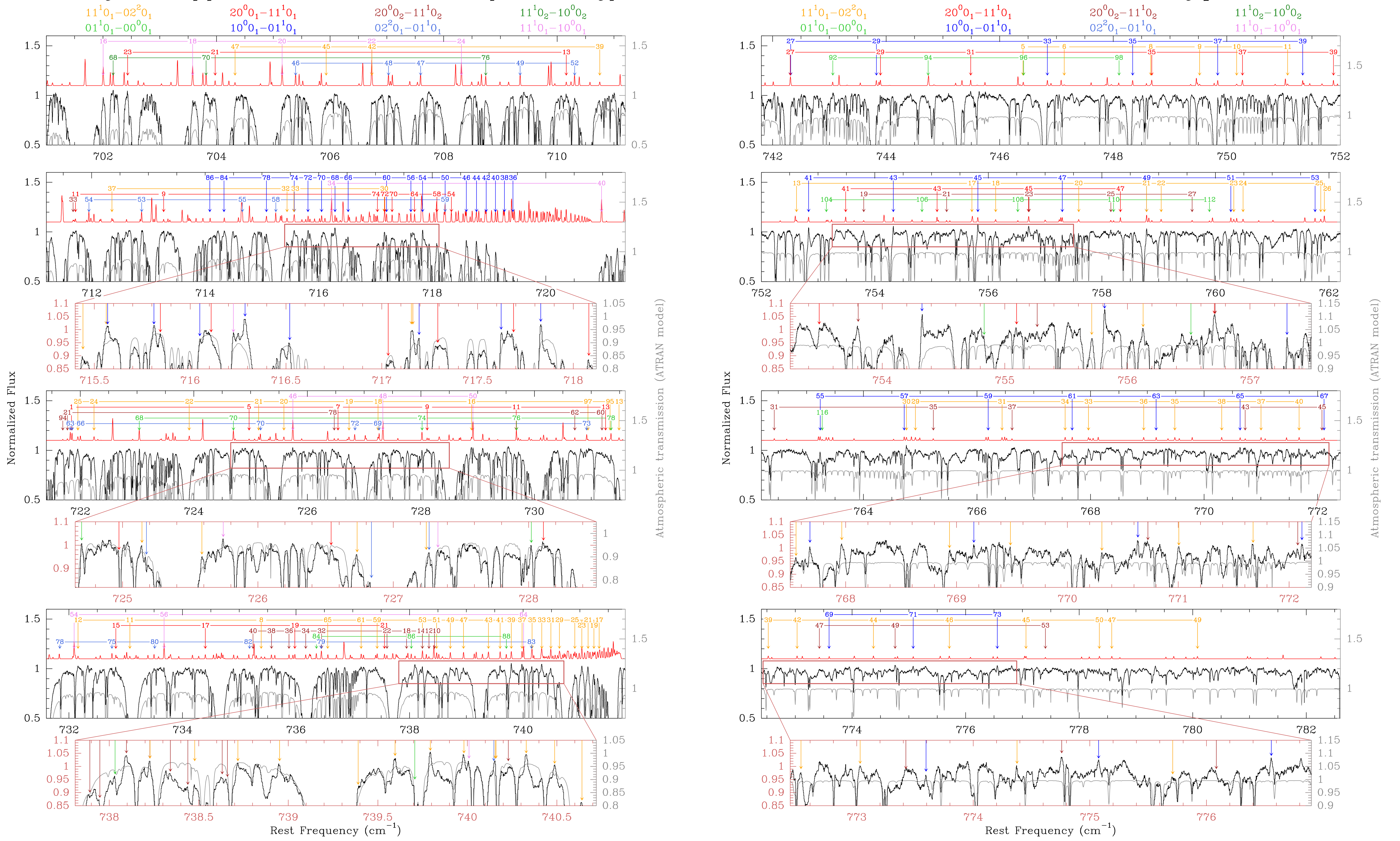

Figure 1.- Spectrum of R Leo in the rest frequency, i.e., corrected of its radial velocity. The CO_2 lines of the bands (notation: $\nu_1\nu_2^\ell\nu_{3,r}$) at the top of the Figure that are clearly detected are plotted in different colors. The branches are not indicated for the sake of clarity. The red synthetic spectrum is a model to the CO_2 emission and the gray spectrum is the atmospheric transmission (ATRAN; Lord 1992). The radial velocity of R Leo with respect to Earth during the observing flight was -22.4 km s^{-1} ($\simeq 0.055$ cm^{-1}/0.001 μm at 740 cm^{-1}/13.514 μm).

Results and conclusions

- About **240 lines from 7 ro-vibrational bands of CO_2** are detected only **in emission** with a maximum intensity of **10% above the continuum** (Figure 1). They are usually found in the blue-shifted wings of stronger telluric CO_2 features, always in absorption. Lines of the fundamental band with $J\gtrsim 70$ and of the hot and combination bands with $J\geq 5$ can be identified in the spectrum. The **highest excitation ro-vibrational level** involved is at $\simeq$ **7000 K**.
- The detected lines are **single-peaked** features centered **at the systemic velocity** and delimited by the terminal gas expansion velocity (Figure 2). The average **deconvolved FWHM is** $\simeq$ **2.5 km s^{-1}**. Most of the lines are formed at the beginning of the acceleration region. The low-J lines of band $11^10_1-10^00_1$ seem to comprise a very narrow peak and a flat-topped contribution, which probably comes from already accelerated gas.
- The **continuum emission** can be described as a **compact black-body** at $\simeq$ **2400 K** (central star) and a **more extended one** at $\simeq$ **850 K** (dust; Figure 3).

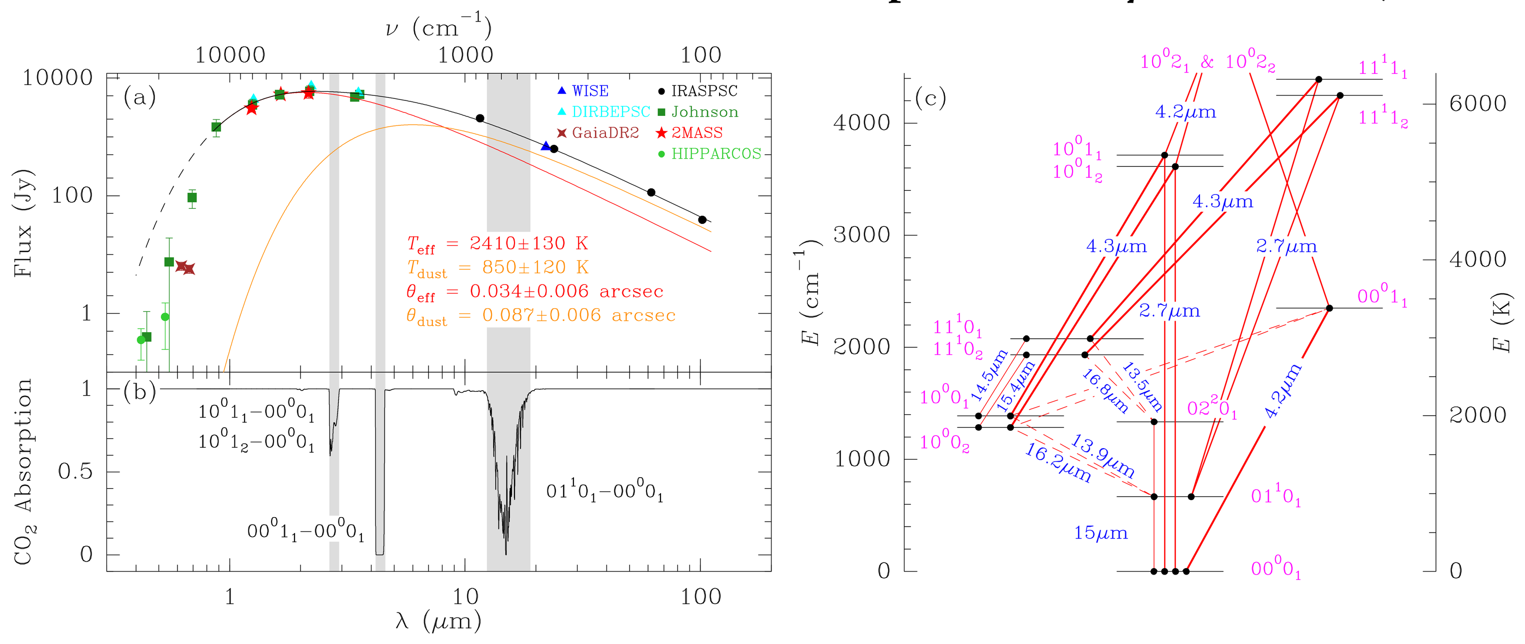

Figure 3.- (*Upper left*) These observations have been complemented with photometric data of the IRAS, WISE, DIRBE, 2MASS, GaiaDR2, and HIPPARCOS catalogs. Additional measures acquired with Johnson filters have also been used. (*Lower left*) CO_2 absorption at 1500 K. (*Right*) Vibrational energy diagram of CO_2 with the most relevant transitions.

- The ro-vibrational diagram shows **three CO_2 populations** with rotational temperatures, T_{rot}, of **550, 1150, and 1600 K** (Figure 4), located at **r** $\simeq$ **2.2, 3.5, and 10R$_\star$** ($1R_\star=0''.028$). The dual component detected in the low-J lines of band $11^10_1-10^00_1$ could be evidence of the gas acceleration. The **bands involving higher energy** vibrational states ($11^10_1-10^00_1$ and $11^10_1-02^20_1$) show **lower values for T$_{rot}$**.
- The **CO_2 column density** is $N_{col}\gtrsim (2.2\pm0.8)\times10^{16}$ **cm^{-2}**.
- The **continuum emission at 2.7 and 4.2 μm excites** a significant fraction of **CO_2 molecules** from the **vibrational ground state** and **01^10_1** to high energy vibrational states thanks to the strong CO_2 bands **$10^01_1-00^00_1$, $10^01_2-00^00_1$, $11^11_1-01^10_1$**, and **$11^11_2-01^10_1$** (Figure 3). Further **de-excitations** populate the vibrational states 10^00_1, 10^00_2, 11^10_1, and 11^10_2.
- States **10^00_1** and **10^00_2** are expected to be **populated closer to the star than 11^10_1** and **11^10_2** because the former are populated from the vibrational ground state and the latter from 01^10_1. The state **01^10_1** is at $\simeq 1000$ K and it is efficiently **excited by continuum emission at 15 μm**, which is **enhanced** at several radii from the star **by the dust emission**. This scenario could explain why the T_{rot} of bands $11^10_1-02^20_1$ and $11^10_1-10^00_1$ are lower than that of $10^00_1-01^10_1$.
- A CO_2 **column density** of $\simeq$ **5×10^{17} cm**$^{-2}$ can be adopted as **typical for AGBs and SRs** with a **high dispersion** of a **factor of 20** (e.g., Markwick et al. 2000; Cami et al. 2000; Baylis-Aguirre et al. 2020). Assuming a kinetic temperature of $2750(1R_\star/r)^{0.7}$ K, a steeper vibrational temperature ($\propto r^{-0.9}$), rotational LTE, and a CO_2 **abundance with respect to H_2 of** $\simeq$ **2.5×10^{-5}**, we estimate the **column density** for R Leo to be $\simeq$ **7×10^{17} cm**$^{-2}$. Up to **80% of CO_2** molecules may be in **vibrationally excited** (Figure 1).
- **SOFIA/EXES** has a **incomparable ability** to observe the **infrared spectrum of molecules in space**, *even if they are abundant in the atmosphere.*

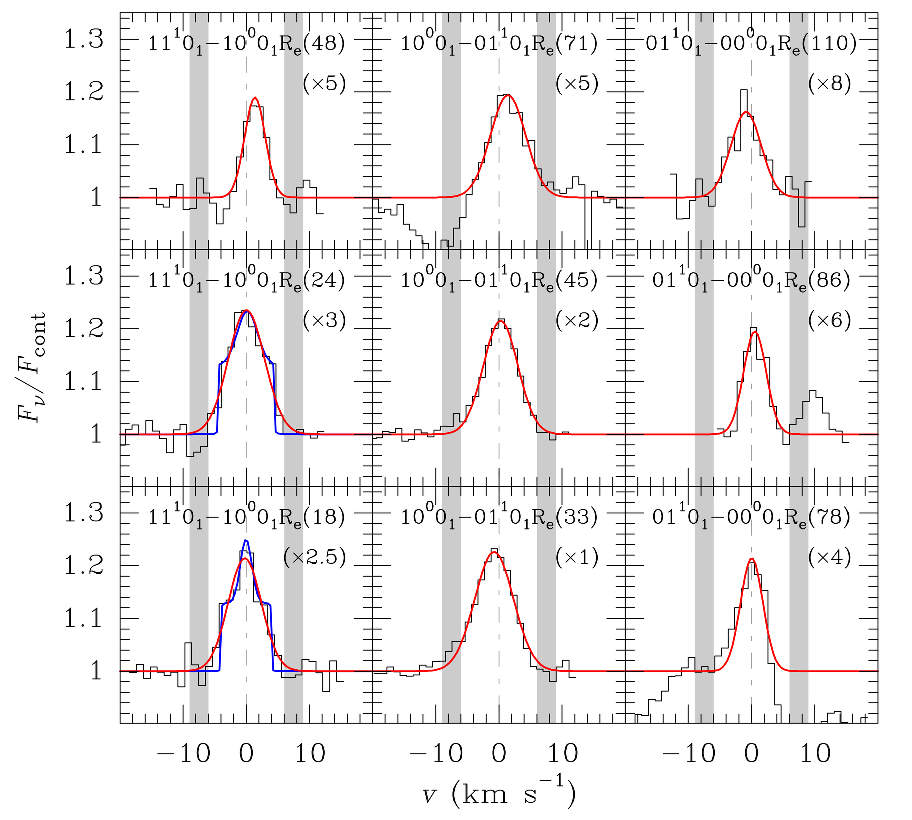

Figure 2.- Lines of the R$_e$ branches of bands $11^10_1-10^00_1$, $10^00_1-01^10_1$, and $01^10_1-00^00_1$. The gray, vertical thick lines represent the terminal gas velocity ranging from 6 to 9 km s^{-1}. The red fits have been done with Gaussians. The blue fits consider a Gaussian and a rectangular function.

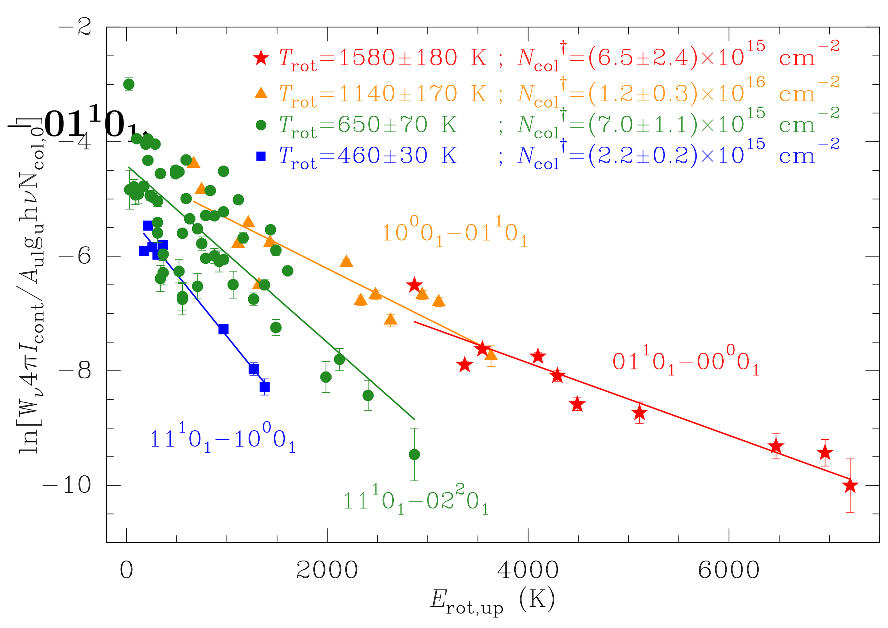

Figure 4.- Ro-vibrational diagram of the strongest observed CO_2 bands. $N_{col}^\dagger=N_{col,vib}\left(\theta_{em}^2/\theta_{cont}^2\right)\left[(\theta_b^2+\theta_{cont}^2)/(\theta_b^2+\theta_{em}^2)\right]$.

The research leading to these results has received funding support from the European Research Council under the European Union's Seventh Framework Program (FP/2007-2013)/ERC Grant Agreement n. 610256 NANOCOSMOS. EJM acknowledges financial support for this work through award #06_0144 which was issued by USRA and provided by NASA. MJR and EXES observations are supported by NASA cooperative agreement 80NSSC19K1701. Based on observations made with the NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA). SOFIA is jointly operated by the Universities Space Research Association, Inc. (USRA), under NASA contract NAS2-97001, and the Deutsches SOFIA Institut (DSI) under DLR contract 50 OK 0901 to the University of Stuttgart.