New Sub-millimeter HCN Lasers in C-rich AGB stars

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Dedicated to the memory of Prof. Karl Menten

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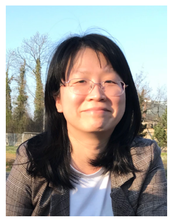
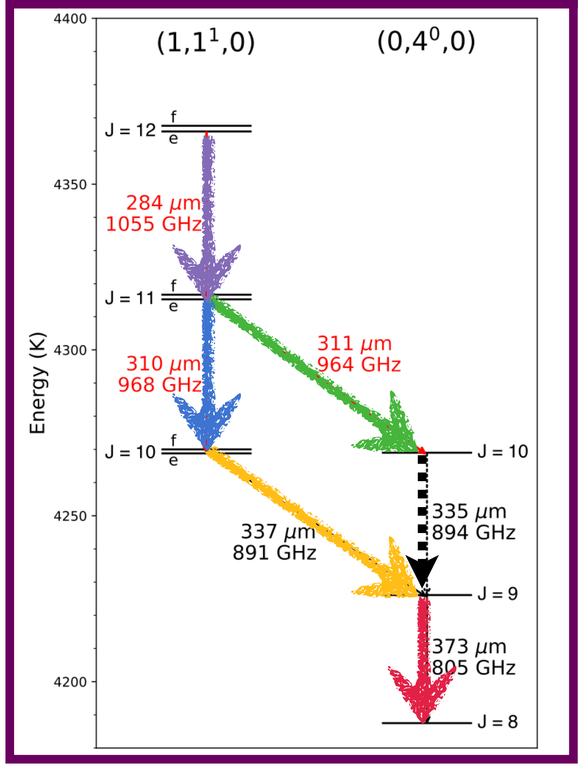


Abstract

HCN is one of the most abundant molecules in the circumstellar envelopes (CSE) of carbon-rich AGB stars. HCN lasers in the Coriolis-coupled system between the (1,1^{1e},0) and (0,4^{0},0) vibrational states (E_{up} > 4200 K), which have been studied in early laboratory spectroscopy. Two intense sub-millimeter laser lines at 805 and 891 GHz were detected in a few carbon stars (Schilke et al. 2000, Schilke & Menten 2003), but the lines above 950 GHz remained unexplored in astronomical contexts due to observational challenges. Using SOFIA/4GREAT observations and Herschel/HIFI archival data, we analyzed six HCN transitions in the Coriolis-coupled system toward eight C-rich AGB stars. **We discovered three new HCN laser transitions at 964, 968, and 1055 GHz.** We investigated the variabilities, excitation, and possible pumping mechanisms of all laser emissions in this system, and found these laser emissions could be the widespread and bright laser species in C-rich AGB stars.

Coriolis-coupled system



SOFIA/4GREAT observations & Herschel/HIFI archives

- **SOFIA / 4GREAT observations** (PI: Karl Menten)
  - > IRC+10216 : 891, 964, 968, 1055 GHz
  - > CIT 6, Y CVn, S Cep: 964, 968 GHz
  - > One flight observations on 2018 Dec. 17
    beam size: 26″ — 31″, Vres ~ 0.15 km/s

- **Archival Herschel / HIFI data**
  - > observations that cover all 6 lines:
    805, 891, 894, 964, 968, 1055 GHz
  - > **8 stars**: IRC+10216, CIT 6, Y CVn, S Cep, IRC+50096, V Cyg, II Lup, CRL 3068
  - > **IRC+10216**: 6 epochs of observations from 2010 May to 2013 Apr. (see spectra below)
  - > beam size: 20″ — 26″, Vres ~ 0.15 km/s

Laser detection overview

> **805**, **891**, **964** GHz: detected in **7** / 8 stars
> **968** GHz: detected in **6** / 8 stars
> **1055** GHz: detected in **5** / 8 stars

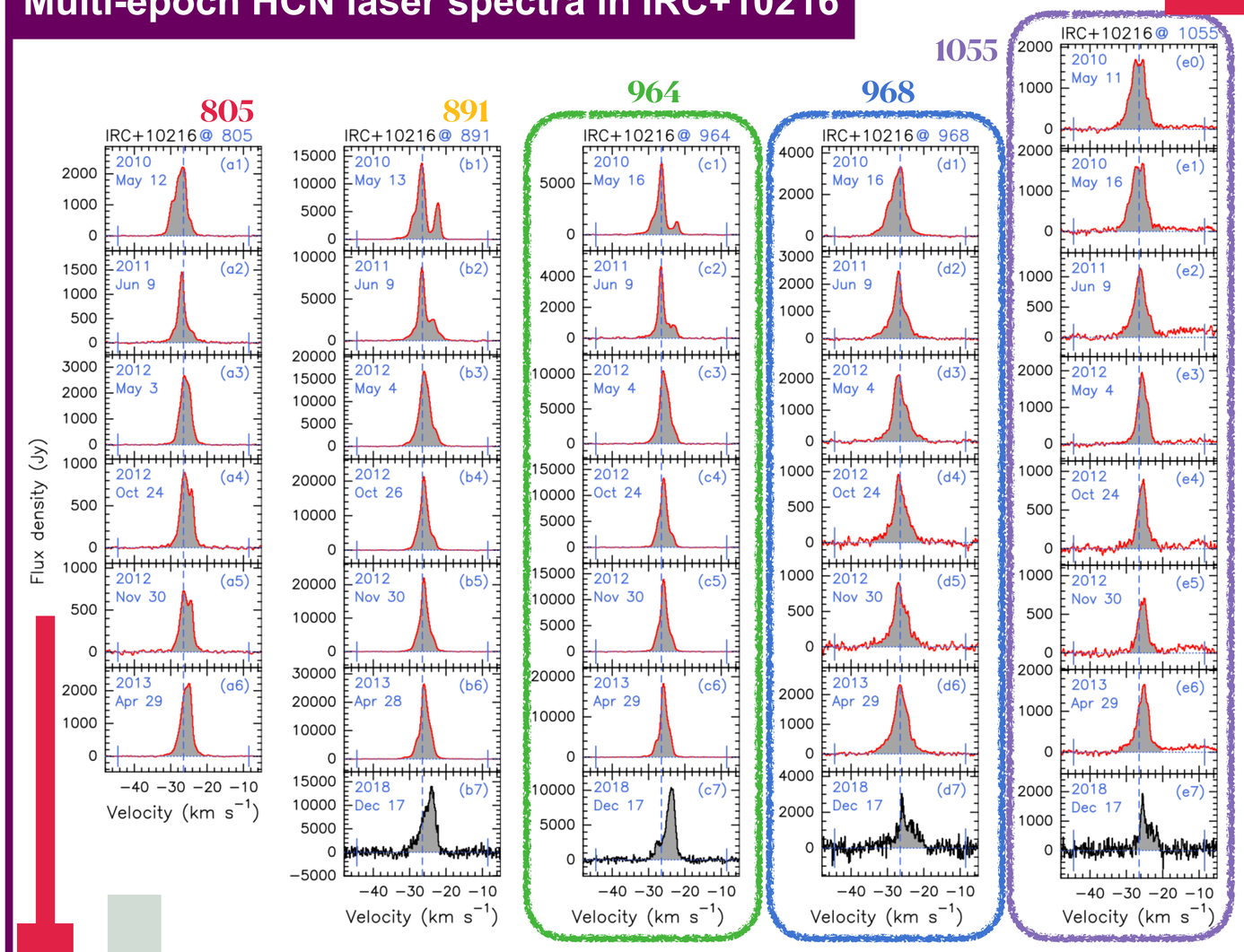
Widespread !

> **894 GHz: 0 star**
> CRL 3068: no HCN laser lines detected

Yang et al. 2025, A&A, 696, A60

Multi-epoch HCN laser spectra in IRC+10216

View spectra by row



NEW HCN laser transitions in space!

Laser excitation

Ranking of laser luminosities in IRC+10216

891 GHz > 964 GHz > 968 GHz > 805 GHz ≈ 1055 GHz

(~10^{44} photons/s) (~1/2 of 891 GHz) (~1/10 of 891 GHz)

Observation findings in 8 C-rich AGB stars

1. 891 GHz laser always strongest
2. 964 GHz laser is similar to 891 GHz laser, 2nd strong

Match the scenario found in early laboratory studies (Maki & Blaine 1964; Lide & Maki 1967)

infer

3. 968 GHz laser stronger than 1055 GHz laser
4. 805 GHz laser co-exists with 891 GHz laser
5. 894 GHz line was not detected in any observed targets

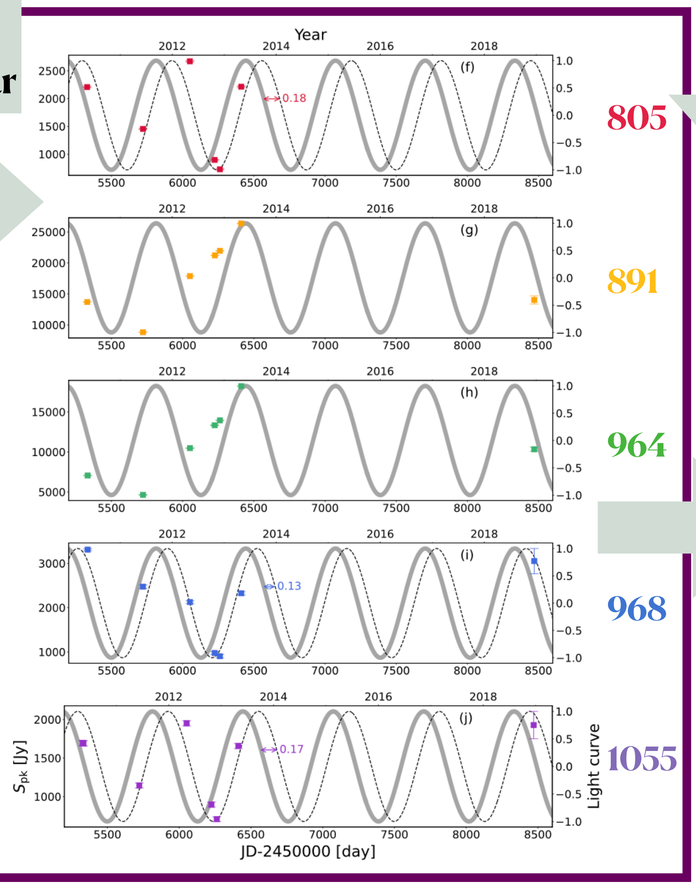
Cross-ladder lasers (891 & 964) dominate the population

View spectra by column

Laser variabilities

891 & 964 GHz laser profiles in the same epoch are more similar

Peak intensity of Laser vs. NIR light curve



Two variation patterns

Cross-ladder lasers (891 & 964 GHz)
do not follow NIR light curve

Rotational lasers (805, 968 & 1055 GHz)
follow NIR light curve with a small lag

Possible pumping mechanisms

1. **Chemical pumping** (i.e. direct formation of HCN molecules in vibrationally excited states) and **radiative pumping** could be important for Cross-ladder lasers (891 & 964 GHz)

2. Rotational lasers (805, 968 & 1055 GHz) may be **modulated by additional collisional and radiative pumping** (driven by periodic shocks and variations in infrared luminosity).

Analogues to vibrationally excited SiO and H_2O masers in O-rich AGB stars

Three key similarities:
widespread, bright, innermost CSE origin