Atomic Clocks in Space: A Search for Rubidium and Cesium Masers in M- and L-Dwarfs

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ABSTRACT

I searched for the ground state 6.8 and 9.2 GHz hyperfine transitions of rubidium and cesium toward M- and L-dwarfs that show Rb and Cs optical resonance lines. The optical lines can pump the hyperfine transitions, potentially forming masers. These spin-flip transitions of Rb and Cs are the principal transitions used in atomic clocks (the $^{133}$Cs hyperfine transition defines the second). If they are detected in stellar atmospheres, these transitions would provide exceptionally precise clocks that can be used as accelerometers, as exoplanet detectors, as probes of the predictions of general relativity, as probes of light propagation effects, and as a means to do fundamental physics with telescopes. Observations of 21 M- and L-dwarfs, however, show no evidence for Rb or Cs maser action, and a previous survey of giant stars made no Rb maser detections.

A RUBIDIUM AND CESIUM PRIMER

Rubidium has atomic number 37 and two common isotopes: $^{85}$Rb (stable) and $^{87}$Rb (49 Gyr half-life); the terrestrial isotopic ratio is 72:28 (Pringle & Moynier 2017). The $^{87}$Rb ground state hyperfine transition at 6.83468261090429(9) GHz (Bize et al. 1999) can form a maser and is often used as an atomic clock. Rb has one valence electron in the $^5S_{1/2}$ ground state, and the primary optical resonance transitions are $^5S_{1/2} \rightarrow ^5P_{1/2}$ and $^5S_{1/2} \rightarrow ^5P_{3/2}$ at 795 and 780 nm. The 6.8 GHz $^{87}$Rb atomic clock maser relies on the hyperfine structure of the $^{85}$Rb optical resonance lines to selectively filter and optically pump the $^{87}$Rb hyperfine ground states, creating a population inversion and promoting maser action (Bender et al. 1958; Davidovits & Novick 1966). The same processes may occur in stellar and sub-stellar atmospheres, producing a natural 6.8 GHz $^{87}$Rb maser.

The analogous hyperfine cesium transition occurs at exactly 9.192631770 GHz; this transition defines the second. Unlike Rb, there is only one stable isotope of Cs, $^{133}$Cs. The optical resonance lines at 852.3 and 894.6 nm correspond to the transitions $^6S_{1/2} \rightarrow ^6P_{3/2}$ and $^6S_{1/2} \rightarrow ^6P_{1/2}$. The pumping of coherent 9.2 GHz Cs emission occurs via collisions with buffer gases of similar pressure to that found in stellar photospheres, seems to be fairly independent of buffer gas species, and increases with temperature (Vanier et al. 1998). Laboratory work was limited by temperature and did not include ions (although this is not an issue for M- and L-dwarf atmospheres), so the expectation for stellar Cs maser action is less certain than it is for Rb (but still favorable).

Astrophysical maser action requires the population inversion of a metastable state, seed photons to amplify (either continuum or spontaneous emission in the maser transition), and a velocity-coherent amplification pathway. These processes can obtain in stellar atmospheres, which can be prodigious emitters of molecular masers such as SiO, OH, and H$_2$O (typically AGB stars). I predict that the conditions in stellar and sub-stellar atmospheres are promising for 6.8 GHz $^{87}$Rb and 9.2 GHz $^{133}$Cs maser action. The Rb I optical pumping lines have been observed in stellar and brown dwarf atmospheres (e.g., Reiners et al. 2007). Cs is usually detected when Rb is detected, and the Cs maser is collisionally pumped.
Pulsars have been used as cosmic clocks with great success (e.g., Backer & Hellings 1986; Burke-Spolaor 2015); detection and subsequent development of Rb and/or Cs masers would provide clocks in new classes of celestial objects. By tying terrestrial standards to clocks in space, one can test basic physics using telescopes, make (weak) tests of general relativity, detect exoplanets via Doppler wobble with unprecedented sensitivity, and, in concert with Gaia proper motions, obtain precise three-dimensional kinematics of stars.

It is worth stressing that all spectral lines are clocks. The power of Rb or Cs hyperfine transitions would lie in their radio frequency maser action, which enables extremely precise Doppler tracking and astrometry compared to any UV, optical, or IR transitions (no bright radio emission lines are known in main sequence stars or brown dwarfs).

ASTROPHYSICAL RUBIDIUM AND CESIUM

The optical resonance lines of alkali metals including Rb I and Cs I have been detected in main sequence stars, brown dwarfs (Manjavacas et al. 2016), giant stars (e.g., García-Hernández et al. 2006), and even a candidate Thorne-Żytkow object in the Small Magellanic Cloud (Levesque et al. 2014). The $^{85}$Rb and $^{87}$Rb lines are blended and cannot be distinguished in optical spectra, but the observed presence of other s-process elements, such as Zr, can be used to infer the presence of $^{87}$Rb when the blended Rb I lines are detected.

Despite the lower abundance of Cs compared to Rb (Lodders 2003), Cs absorption lines can be optically thick. Velocity-coherent column density is key for maser action, and stellar atmospheres satisfy this requirement; the question for maser production is whether the pumping of $^{87}$Rb or $^{133}$Cs is quenched by collisions. It is worth noting that masers have almost always been discovered rather than predicted; they amplify small-scale physical conditions that may not be representative of the bulk properties of a gas. Addressing the possibility of Rb or Cs masers in stellar atmospheres therefore requires observations. A small Green Bank Telescope survey of giant stars found no 6.8 GHz $^{87}$Rb emission (Darling 2018), so I turn to low-mass stars and brown dwarfs, which provide less distance-dimming and more practical scientific applications for maser lines, including exoplanet detection and characterization.

OBSERVATIONS

I selected a sample of 13 M-dwarfs and 8 L-dwarfs where Rb I and Cs I are prominent in SDSS DR16 optical spectra (Ahumada et al. 2020), indicating these elements are abundant and that the maser pumping lines are optically thick. Using the NSF’s Karl G. Jansky Very Large Array$^2$ (VLA), I searched for the 6.8 GHz $^{87}$Rb and 9.2 GHz $^{133}$Cs lines. VLA observations used the C configuration with integration times of $\sim$10 min, 3 s sampling, and dual circular polarizations. Bandpasses with 3.91 kHz (0.17 km s$^{-1}$) channels spanning 8 MHz (351 km s$^{-1}$) were centered on the 6.83468261 GHz $^{87}$Rb, and 6.66852 GHz CH$_3$OH transitions, appropriately Doppler shifted to the velocity of each target. The 9.19263177 GHz Cs observations used 5.208 kHz (0.17 km s$^{-1}$) channels spanning 16 MHz (522 km s$^{-1}$). Synthesized beams ranged from 2.6′′×2.0′′ to 7.3′′×2.6′′. I used CASA (McMullin et al. 2007) for interferometric flagging, calibration, and imaging. Spectral cubes were polarization-averaged and smoothed to 1 km s$^{-1}$ to achieve 2 mJy rms noise. No continuum was subtracted from the cubes.

RESULTS AND CONCLUSIONS

I searched for emission features over a broad velocity range ($\pm$125 km s$^{-1}$), taking into account the sometimes high proper motions of the targets. No credible maser features were identified. Table 1 lists the targets, SDSS spectra, and the rms noise of the non-detected transitions.

These results suggest that Rb and Cs masers are unlikely to occur frequently in M- and L-dwarf atmospheres. A survey of 10 giant stars and two globular clusters for the 6.8 GHz $^{87}$Rb maser by Darling (2018) likewise made no detections. I suggest that the search should continue, perhaps toward other types of stars and in the interstellar medium.

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Facilities: VLA

Software: CASA (McMullin et al. 2007)

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Table 1. Observations and Results

| Star                  | SDSS Spectrum\(^a\) | Coordinates       | Spectral Type | SDSS Velocity\(^b\) | \(^{87}\)Rb rms\(^c\) | \(^{133}\)Cs rms\(^c\) | CH\(_3\)OH rms\(^c\) |
|-----------------------|----------------------|-------------------|---------------|----------------------|---------------------|---------------------|----------------------|
| SDSS J000127.84−094209.6 | 7167-56604-0196       | 00:01:27.84 −09.42.09.73 | M       | −4.4                | 2.9                 | 2.1                 | 3.0                 |
| 2MASS J00191165+0003176 | 4218-55479-0989       | 00:19:11.64 +00.30.17.66 | M       | 6.7                 | 3.1                 | 2.0                 | 3.2                 |
| SDSS J002226.64+000023.3 | 4219-55480-0199       | 00:22:26.63 +00.00.23.06 | M       | −9.7                | 2.9                 | 2.1                 | 3.0                 |
| Gaia DR2 253478022797349728 | 3735-55209-0976     | 01:08:46.43 +00.04.06.94 | M       | −72.6               | 2.4                 | 2.5                 | 2.4                 |
| SDSS J011453.90+141914.3 | 4664-56192-0948       | 01:14:14.91 +14.19.14.28 | M       | −32.0               | 2.5                 | 2.4                 | 2.4                 |
| SDSS J012418.33+002242.0 | 4228-55484-0889       | 01:24:18.33 +00.22.42.05 | M       | −27.0               | 2.4                 | 2.6                 | 2.4                 |
| 2MASS J01325911+131248.7 | 4666-55832-0755       | 01:32:59.12 +13.12.48.27 | M       | −3.5                | 2.5                 | 2.4                 | 2.5                 |
| SDSS J015450.56−010610.5 | 4233-55449-0242       | 01:54:50.68 −01.06.11.01 | M       | −19.8               | 2.5                 | 2.5                 | 2.4                 |
| SDSS J023100.81+000855.9 | 3647-55484-0199       | 02:31:00.82 +00.08.55.99 | M       | −45.5               | 2.7                 | 2.7                 | 2.7                 |
| SDSS J023402.03+000623.7 | 3744-55484-0199       | 02:34:02.07 +00.06.22.74 | M       | −49.3               | 2.4                 | 2.5                 | 2.3                 |
| 2MASS J08054990+1312487 | 4486-55588-0118       | 08:05:49.89 +13.12.48.76 | L       | −15.2               | 2.5                 | 2.4                 | 2.6                 |
| SDSS J08107574+182404.8 | 4486-55588-0118       | 08:17:57.49 +18.24.04.99 | L       | 4.5                 | 2.6                 | 2.4                 | 2.7                 |
| SDSS J082906.61+145620.7 | 4503-55563-0828       | 08:29:06.60 +14.56.19.47 | M       | −5.0                | 2.6                 | 2.4                 | 2.7                 |
| SDSS J093155.75+014330.7 | 4903-55579-0474       | 09:35:58.22 +01.43.30.54 | M       | 8.7                 | 2.7                 | 2.4                 | 2.8                 |
| 2MASS J10433323+102447.0 | 5284-55866-0967       | 10:43:33.34 +10.24.40.20 | L       | −11.4               | 2.6                 | 2.4                 | 2.7                 |
| 2MASS J10224821+582545.3 | 7089-56604-0444       | 10:22:46.83 +58.25.35.19 | L       | 15.3                | 2.8                 | 2.7                 | 2.9                 |
| SDSS J093155.75+014330.7 | 5350-56009-0554       | 10:39:47.24 +15.12.51.06 | L       | 6.3                 | 3.1                 | 2.6                 | 3.3                 |
| SDSS J221451.86+004349.9 | 4200-55499-0873       | 22:14:51.86 +00.43.50.00 | M       | −73.0               | 2.6                 | 2.1                 | 2.7                 |
| 2MASS J22585897+152046.1 | 6140-56189-0118       | 22:58:58.87 +15.20.45.06 | M       | −57.6               | 2.4                 | 2.1                 | 2.6                 |
| 2MASS J2352533+094105.6 | 7166-56602-0319       | 23:52:25.39 −09.44.17.52 | M       | −89.9               | 2.7                 | 2.2                 | 2.9                 |

\(^a\)SDSS plate-MJD-fiber.

\(^b\)Heliocentric optical velocity from SDSS model fit.

\(^c\)Noise per 1.0 km s\(^{-1}\) channel.

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