Future Astrometry with ALMA to characterise extra-solar planet orbits

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Abstract. The most complete catalogue of nearby stars by Gliese and Jarheiss (1991) is used to find that the thermal emission of the photospheres of 446 nearby stars can be detected by the future millimeter array ALMA. This array has a theoretical astrometric precision of 0.1 milliarcsecond. A long-term astrometric observation programme (≥10 yr) of these stars would be sensitive to wobbles caused by the gravitational pull of possible unseen planets. Such a programme would probe minimum planetary masses as low as 0.1 Jupiter for an orbital period of 10 years. We provide the histogramme of these minimum masses for the 446 ALMA stars.

1. Introduction

Discovery of Jupiter-mass planets around other stars by the radial velocity technique (Doppler) since 1995 has been one of the highlights of the last decade in astronomy. Astrometry, similarly to the radial velocity technique, is an indirect method that detects the reflex motion (wobble) of the central star caused by the gravitational pull of the orbiting planet(s). Even when direct imaging of extra-solar planets is routine in the future, high-precision Doppler and astrometry will still be used to measure key parameters, e.g. masses, mutual inclinations and node of orbits to characterise planetary systems. These last two parameters yield importantly the degree of coplanarity of orbits in multiple planet systems.

ALMA is an interferometric array of 64 antennas operating at radio millimeter wavelengths that is planned for construction at Chajnantor (altitude = 5000 m) in Chili. This ground-based facility will be completed in 2010.

We searched the stars that can be detected by ALMA at millimeter wavelengths in the most complete catalogue of Nearby Stars (CNS3 3rd Edition) by Gliese and Jarheiss (1991). We assess the astrometric potential of ALMA for indirect detection of extra-solar planets possibly orbiting these stars.
2. The catalogue CNS3 of Nearby Stars

There are 3461 stars in the CNS3 that are mostly at \( \leq 25 \) pc and have spectral type and magnitude V measured. There are 341 additional stars lacking either spectral type or magnitude V. The CNS3 is more complete than Hipparcos for nearby stars but is thought still uncomplete even within 10 parsecs.

| Spectral Type | Nber of stars in the whole CNS3 (mostly \( d \leq 25 \) pc) | Nber of stars in the CNS3 at \( d \leq 10 \) pc | Nber of stars detectable by ALMA | Fraction of the CNS3 |
|---------------|-------------------------------------------------|---------------------------------|---------------------------------|----------------------|
| O             | 0                                               | 0                               | 0                               | 0 %                  |
| B             | 3                                               | 1                               | 2                               | 66 %                 |
| A             | 69                                              | 5                               | 54                              | 78 %                 |
| F             | 266                                             | 11                              | 158                             | 59 %                 |
| G             | 495                                             | 30                              | 125                             | 35 %                 |
| K             | 824                                             | 57                              | 71                              | 9 %                  |
| M             | 1804                                            | 291                             | 36                              | 2 %                  |
| Total         | 3461                                            | 395                             | 446                             | 13 %                 |

Table 1: Distribution of spectral type in the catalogue CNS3. Distribution of stars detectable by ALMA above 0.1 milliJansky at 345 GHz. For some stars, the catalogue provides only approximate spectral types that have been interpreted in our analysis as the following: a-f=F0, f=F5, f-g=G0, g=G5, g-k=K0, k=K5, k-m=M0, m=M2, m+=M6.

3. Thermal emission of stars detectable by ALMA and astrometric precision

ALMA can detect the thermal emission from the photospheres of some stars at radio millimeter wavelengths. This provides a well-defined surface whose radio centroid position can accurately track the reflex motion of an unseen companion. Is a spotted photosphere a limiting factor? If star spots were present there would be an additional position modulation with the known rotation period of the star. If a G dwarf were covered by spots over 0.2% of its surface and the differential temperature photosphere-spot be \( \Delta T=1000 \) K, typical of the Sun, the astrometric modulation amplitude \( \xi \) would be \( \sim 0.1 \) μarcsec at 10 pc, i.e. negligible. For an M dwarf covered over 70% and \( \Delta T=1000 \) K, the amplitude \( \xi \) would be \( \sim 35 \) μarcsec at 10 pc.

We have computed the thermal flux densities at 345 GHz for the photospheres of all the stars of the CNS3. The frequency 345 GHz is the optimum sensitivity of ALMA for this project. This calculation is based on the Planck radiation law; the brightness is \( B(\nu, T) = \frac{2\hbar \nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1} \); the unit of \( B(\nu, T) \) is \( \text{W m}^{-2} \text{ Hz}^{-1} \text{ Rd}^{-2} \) with the proper constants. The spectral types from the catalogue were used to derive the effective temperatures \( T \) and the linear diameters of the stars. The distance was taken also from the catalogue to compute the photospheric surface \( \Omega \) in Rd² and the flux density \( F_\nu = B(\nu, T) \times \Omega \).
The sensitivity of ALMA yields a signal-to-noise SNR of 30 for the observation of a solar type star ($T_{\text{eff}}=6500$ K and diameter = $2R_\odot$) at 10 pc in one-hour of integration at 345 GHz ($\lambda = 0.87$ mm).

The theoretical astrometric precision of ALMA is:

$$\sigma_{\alpha,\delta} = \frac{1}{2\pi} \frac{1}{SNR} \frac{\lambda}{B} = 0.1 \text{ milliarcsecond}$$

for baseline length $B = 10$ km, $\lambda = 0.87$ mm and SNR=30. This is 10 times better than the astrometric precision of Hipparcos.

Proper calibration scheme should be developed to monitor the atmospheric phase fluctuation in order to reach this theoretical precision. This is a challenging issue.

4. RESULTS

4.1. 446 nearby stars observable astrometrically by ALMA

We have found that 446 nearby stars of the CNS3 have a flux density $\geq 0.1$ mJy at 345 GHz and, hence, are detectable by ALMA. The signal-to-noise ratio SNR 30, required for the astrometric precision of 0.1 milliarcsecond, can be reached with an integration time of a few hours for these stars by using the full bandwidth (16 GHz) of the array and both polarizations. The declination cutoff $\delta < +35^\circ$ was also used in this study because ALMA is located at Chajnantor in Chili. The last 2 columns in Table 1 show the spectral types of these ALMA stars and their fractions of the whole CNS3. The histogram of all the integration times (for an SNR=30) of this sample of stars is in Figure 1.

4.2. Minimum masses for unseen planets detectable astrometrically by ALMA

The amplitude of the wobble of the central star due to the gravitational pull of the planet in a circular orbit is:

$$\theta = \frac{m}{M} \frac{a}{d} = \frac{m}{d} \left( \frac{P}{M} \right)^{2/3}$$

where $\theta$ is in arcsecond, $a$ in AU, $P$ in years, $d$ in pc, $m$ and $M$, the masses of the unseen companion and of the central star, in $M_\odot$.

We have computed the mass $m$ of the companion with the following assumptions:
1) astrometric precision of the individual ALMA observation $\sigma = 0.1$ milliarcsecond.
2) the wobble $\theta$ detectable by several observations over at least an orbital period is $\theta = 1\sigma$.
3) Orbital period $P = 10$ years
4) Observation program at least as long as $P = 10$ years.

The histogram below summarises the range of minimum masses that can be probed by ALMA.
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Figure 1. **Left:** histogramme of minimum masses detectable astrometricly by ALMA for possible unseen companions orbiting nearby stars. The corresponding astrometric programme must last at least 10 years and maintains an astrometric precision of 0.1 milliarcsecond. **Right:** the integration times required to reach the theoretical astrometric precision of 0.1 milliarcsecond by ALMA.

5. Conclusion

We found that 446 nearby stars of the Gliese & Jarheiss catalogue can be observed astrometricly by ALMA at radio millimeter wavelengths. The theoretical astrometric precision of 0.1 milliarcsecond can be reached in a reasonable integration time ($\leq$ a few hours) for these stars. The challenge to reach this precision is the monitoring of the rapid phase fluctuations caused by the atmosphere even at an altitude of 5000 m. Strategies of observation, *e.g.* Fast-Switched Phase referenced observations, or real-time measurements of these fluctuations are being tested. This astrometric potential has the power of measuring orbital parameters and masses of unseen companions as small as 0.1 Jupiter for the closest stars with an observation program of 10 years. The ALMA array should start operation in 2006 with 8 antennas and gradually increases to 64 antenna by 2010.

ALMA will also be a powerful instrument to image protoplanetary disk, circumstellar debris disk and exozodiacal light (see Wootten in these Proceedings).
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Bibliographical references:
Gliese, W., Jarheiss, H., 1991, http://www.ari.uni-heidelberg.de/aricns/files/cns3type.htm