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Authors: Qian, Lei, Qian, Lei

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Full Text

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The Distance to Exoplanet Systems with Imaging and Spectral Measurement

Lei Qian[1,2,3,4]

[1]National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China; lqian@nao.cas.cn

[2]College of Astronomy and Space Sciences, University of Chinese Academy of Sciences, Beijing, 100101, People's Republic of China

[3]Key Laboratory of Radio Astronomy, Chinese Academy of Sciences, Beijing 100101, People's Republic of China

Abstract

The distance D to an exoplanet system with imaging and spectral measurement can be obtained by using the orbit as a ruler. The measurement of the distance to a typical exoplanet system with imaging and spectral measurement can be accurate to $\delta D/D \sim 0.2$, if the orbital velocity of the planet can be measured accurately to ~ 3 km/s.

Key words: stars: distances, techniques: high angular resolution, techniques: spectroscopic

1 Introduction

Distance is a parameter of fundamental importance in astrophysics. Distances of different magnitudes are measured with different methods. For objects in the solar system, radar ranging can be used. For nearby stars, trigonometric parallax is usually employed. At larger distances, standard candles and standard rulers are often applied. The redshift-distance relation is also used to estimate distance, but it is model-dependent.

In distance measurements with standard rulers, galaxies with megamaser disks are typical examples. The angular-size distance has been measured for, e.g., NGC 4258 ($7.60\pm0.17\pm0.15$ Mpc, Humphreys et al. 2013), UGC 3789 (49.9 ± 7.0 Mpc, Braatz et al. 2010), NGC 6264 (144 ± 19 Mpc, Kuo et al. 2013), CGCG 074-064 ($87.6^{+7.9}_{-7.2}$ Mpc, Pesce et al. 2020), and NGC 5765b (123.6 ± 11.6 Mpc, Gao et al. 2016). This method relies on the measurement of the orbital motion of the maser disk around the central black hole and the angular size of this disk. This method can also be applied to other systems where the size of the orbit and the orbital motion can be measured. Besides binary stars, the distance to stars with planetary systems can also be determined using this approach.

2 Methods

By monitoring the spectra of a planet orbiting a star, the orbital velocity v at different orbital phases can be obtained. From the phase-resolved orbital velocity, the acceleration a can be determined. The orbital velocity is given by $v=\sqrt{GM/r}$, where G is the gravitational constant, M is the mass of the star, and r is the orbital radius of the planet. On the other hand, the acceleration can be written as $a=v^2/r=GM/r^2$. With these two equations, we can solve for r and M:

$$r=\frac{v^2}{a},\quad M=\frac{v^4}{Ga}.$$

With imaging observations, we can measure the angular size of the orbit, θ. The distance D can then be obtained as $D=r/\theta$.

3 The Accuracy of Mass and Distance Measurements

The accuracy of mass and distance measurements depends on the accuracy of measurements of orbital size, velocity, and acceleration, $\delta\theta$, δv, and δa. The relative accuracies can be written as:

$$\frac{\delta r}{r}=\sqrt{\left(\frac{\delta v}{v}\right)^2+\left(\frac{\delta a}{a}\right)^2},$$

$$\frac{\delta M}{M} = \sqrt{\left(\frac{\delta \theta}{\theta}\right)^2 + \left(\frac{\delta v}{v}\right)^2 + \left(\frac{\delta a}{a}\right)^2}.$$

The acceleration can be calculated from the orbital velocity and the orbital period T. So:

$$\frac{\delta a}{a} = \sqrt{\left(\frac{\delta v}{v}\right)^2 + \left(\frac{\delta T}{T}\right)^2}.$$

Usually, $\delta T/T \ll \delta v/v$.

To achieve measurements of the mass and distance with $\delta D/D \sim 0.2$ and $\delta M/M \sim 0.2$, the relative errors $\delta\theta/\theta$ and $\delta v/v$ should be smaller than ~ 0.1. For imaging observations, the accuracy of measuring the angular size of the orbit is determined by the angular resolution of the telescope. The angular resolution of optical interferometers can reach 1 mas (GRAVITY Collaboration et al. 2017).

For a typical planetary orbit like Earth's orbit at a distance of ~ 100 pc, the distance can be measured to an accuracy of $\delta D \sim 20$ pc if the orbital velocity can be measured to an accuracy of ~ 3 km/s (0.05 Å at 5000 Å). With current telescopes, it is still difficult to reach this precision (Holmberg & Madhusudhan 2023).

4 Discussion

Based on imaging and spectral observations, the distance to an exoplanet system can be measured. The mass of the central star is also measured simultaneously. The measurement of the distance to a typical exoplanet system with imaging and spectral measurement can be accurate to $\delta D/D \sim 0.2$ if the orbital velocity can be measured to an accuracy of ~ 3 km/s. At the same time, the mass of the central star can be measured to an accuracy of $\delta M/M \sim 0.2$.

The methods of distance and mass measurement proposed in this work are independent of conventional methods. They can serve as auxiliaries to other methods.

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Note: Figure translations are in progress. See original paper for figures.