Survey for Transiting Extrasolar Planets in Stellar Systems (STEPSS): The Frequency of Planets in NGC 1245

Christopher J. Burke\textsuperscript{1}, D. L. DePoy\textsuperscript{1}, B. Scott Gaudi\textsuperscript{2}, J. L. Marshall\textsuperscript{1}, Richard W. Pogge\textsuperscript{1}

\textsuperscript{1}Department of Astronomy, The Ohio State University, Columbus, OH 43210-1173
\textsuperscript{2}Hubble Fellow, School of Natural Sciences, Institute for Advanced Study, Einstein Drive, Princeton, NJ, 08540

Abstract. We present first results from the Survey for Transiting Extrasolar Planets in Stellar Systems (STEPSS). Our goal is to assess the frequency of close-in extrasolar planets around main-sequence stars in several open clusters. By concentrating on main-sequence stars in clusters of known (and varied) age, metallicity, and stellar density, we will gain insight into how these various properties affect planet formation, migration, and survival. We show preliminary results from our 19 night photometric campaign of the old, solar metallicity cluster NGC 1245. Taking into account the photometric precision, observational window function, transit probability, and total number of stars monitored, we estimate that we should be able to probe planetary companion fractions of \(< 1\%\) for separations of \(a < 0.03\) AU. If 1\% of the stars in the cluster have Jupiter-sized companions evenly distributed in \(\log a\) between 0.03 and 0.3 AU, we expect to find \(\sim 2\) transits. A preliminary search of our light curve data has revealed a transit with a depth \(\sim 4\%\). Based on its shape, it is likely to be a grazing binary eclipse rather than a planetary transit, emphasizing the need for high temporal resolution in transit surveys.

1. Introduction

The recent detections of candidate low-mass companions to local disk stars via transits by several groups has verified the possibility of discovering statistically significant numbers of extrasolar planets through ground based transit surveys (Udalski et al. 2002, Mallen-Ornelas et al. 2003). Although such surveys will provide valuable information about the types of planetary systems that exist, it will be difficult to piece together the dynamical, chemical, and evolutionary history of the parent stars. The parent stars’ physical properties are particularly important since radial velocity surveys for low-mass companions have revealed the trend of the fraction of stars with planets increases as a function of the metallicity of the parent star. The interpretation of this trend is unclear and more information is needed.
Simple stellar systems, such as globular clusters and open clusters, are an excellent laboratory for transit surveys. Such fields provide $\sim 10^3-5$ stars of the same age and metallicity. Interpretation of the null result for the metal-poor globular cluster 47 Tuc (Gilliland et al. 2000) has been complicated by the possible effects of the dense stellar environment on planet formation and survival. Therefore, we are concentrating on metal-rich, sparser open clusters. By observing main-sequence stars in 4-5 open clusters of known (and varied) age, metallicity, and stellar density, we will gain insight into how these various properties affect planet formation, migration, and survival. Our primary instrumentation is the MDM 8192x8192 4x2 Mosaic CCD imager. In combination with the MDM 2.4m telescope it yields a 25x25 arcmin$^2$ field of view with 0.18"/pixel. The Ohio State University has access to a 25% share of the MDM facility; in 2001 we were granted 19 nights on the 2.4m, we have been granted $\sim 60$ nights during Fall 2002, and we expect to obtain 20-40 nights for each cluster in the future with the same instrumental setup.

2. Observations, Analysis and Preliminary Results for NGC 1245

In Oct. 2001 we obtained data over 19 nights for the open cluster NGC 1245, an old ($\sim 1$ Gyr), solar-metallicity cluster with $\sim 1500$ members. We lost 4 nights to inclement weather and the remainder were non-photometric, resulting in a total of 960 $I$-band images. We performed the photometric reduction using the DoPhot PSF fitting package. Differential light curves for individual target stars were derived by locating 13 optimal comparison stars close to each target. We plan to test difference imaging techniques in the future. The points in Figure 1(a) show the RMS scatter in the light curves as a function of $I$-magnitude. The lower, tight sequence of points in Figure 1(a) shows the expected photon noise. At the faint end, the RMS scatter is only $\sim 15\%$ larger than the photon limit.
Figure 2. Light curves for a transit candidate observed on two separate nights. Unfortunately, this is likely to be a grazing binary eclipse.

At the bright end, there is a systematic error $\sim 0.26\%$, which we suspect is due to flat-fielding errors. The lines in Figure 1(a) represent the transit depth for a 1.3 and $1.0 \, R_{\text{Jup}}$ planet. Figure 1(b) shows the ratio between the transit depth of a $1.0 \, R_{\text{Jup}}$ planet and the light curve RMS scatter. There are $\sim 4300$ stars with sufficient S/N to detect a $R_{\text{Jup}}$ transit. Also shown in this figure is the estimated mass of the parent star assuming a 1 Gyr, solar-metallicity population at 2.5 kpc and E(B-V)=0.26. We estimate 35% of these stars to be cluster members.

A preliminary search through the data has revealed a transit candidate with a depth $\sim 4\%$. We observed the transit on two separate nights and the light curves are shown in Figure 3. Unfortunately, the transit is unlikely to be a planetary transit, since the transit shape is indicative of a grazing binary eclipse. Planetary transits tend to be boxier in shape with more rapid ingress and egress durations and flat-bottom eclipses (Seager & Mallén-Ornelas 2003). However, this example demonstrates the extreme importance of sufficient time resolution in transit surveys in order to easily discard signals that can be confused with planetary transits.

3. Expected Transit Results and Future Work

We calculate our sensitivity to planetary transits using the formalism outlined in Gaudi (2000). Taking into account the cluster luminosity function, distance, and reddening, our observational photometric sensitivity and window function, and assuming that 1% of stars have $R_{\text{Jup}}$ companions evenly distributed in log semi-major axis between 0.03 and 0.3 AU, we expect to detect $\sim 2$ transits in the NGC 1245 data set. The curves in Figure 3(a) show the 95% upper confidence limits we can place on the fraction of stars with planets for a given configuration of planetary companion separation versus radius. For instance, based on our data obtained for NGC 1245 and a null result, we can exclude greater than 10% of the cluster members having a Jupiter-sized object orbiting within 0.1AU. Figure 3(b) shows the theoretical limits if we had observed NGC 1245 for 40 nights, with 8 hours each night, using the identical instrumental setup. Such results may be achieved with our upcoming 60 nights (30 on MDM 2.4m and 30
Figure 3. (a) Expected 95% upper limits on fraction of stars with planets for NGC 1245. (b) Theoretical upper limits if we had observed NGC 1245 for 40 nights, with 8 hours each night, using the identical instrumental setup.

We have demonstrated that we can easily achieve the photometric precision necessary to detect Jupiter-sized transits around main-sequence stars. In light of the uncertain radial velocity results of the fraction of stars with planets as a function of metallicity, our theoretical expectations show that even without the discovery of planetary transits our survey will place interesting constraints on this relation for a population of determinable metallicity, age, and stellar density. We emphasize the importance of sufficient time resolution in transit surveys, as has been demonstrated by other surveys (Mallen-Ornelas et al. 2003). We will continue to optimize our transit detection methods to search for lower amplitude ($\lesssim 1\%$) transit signals.

Acknowledgments. This work was supported by NASA through a Hubble Fellowship grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

References

Gaudi, B. S. 2000, ApJ, 539, L59
Gilliland, R. L. et al. 2000, ApJ, 545, L47
Mallen-Ornelas, G. et al. 2003, ApJ, submitted (astro-ph/0203218)
Udalski, A. et al. 2002, Acta Astronomica, 52, 1
Seager, S., & Mallen-Ornelas, G. 2003, ApJ, submitted (astro-ph/0206228)