

EXOPLANET SCIENCE WITH PAN-STARRS

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Abstract. So far few exoplanet transits have been found. The occultation of the planet orbiting HD 209458 has provided the density, mass and size of the planet, demonstrating the advantages of this technique. Several experiments are currently underway to search for transits in bright stars (e.g. OGLE, Vulcan and WASP from the ground, Corot and Kepler from space). The characteristics of Pan-STARRS (sensitivity, wide-field, and rapid cadence) provide a unique niche in the search for exoplanet transits. We show that Pan-STARRS will allow to search for transits of hot jupiters in orbit around low-mass stars of open clusters, and of terrestrial sized planets in the habitability region of very low-mass stars and brown dwarfs. We estimate that in 0.1 Pan-STARRS years we could detect about 100 transits in the open cluster NGC 6791, and in a similar amount of time we would set strong constraints to the frequency of habitable planets orbiting very low-mass stars and brown dwarfs, or detect a few of them. This program requires intensive cadence monitoring of specific regions in the sky over timescales of a few weeks. R filter is the preferred choice for stars in clusters, and I filter for brown dwarfs.

1 Introduction

The last six years have witnessed considerable progress in the search for extrasolar planetary systems. Starting with 51 Peg (Mayor & Queloz 1995), the number of extrasolar planets has increased to about 100 in only 7 years. A few planetary systems have also been discovered (e.g., Marcy et al. 2001). Free-floating planets have recently been reported, indicating a variety of processes of planetary formation and evolution (Zapatero Osorio et al. 2002).

So far high-precision radial velocities remain the only technique that has succeeded in detecting a significant sample of planets orbiting solar-type stars (Marcy, Cochran and Mayor 2000). As a result, our knowledge of the population of extrasolar planets is biased to short period giant planets and limited to nearby stars. It is extremely important to carry out complementary studies with a variety of techniques to survey the population of extrasolar planets in different galactic environments and in a variety of primary masses.

The first example of a transiting extrasolar planet was HD 209458b (Charbonneau et al. 2000; Henry et al. 2000). The orbital period of the planet is 3.5 days, the transit lasts 3.07 hours (3.6% of the orbital period), and the light of the star diminishes by a little less than 2%. This discovery has enabled the first secure mass determination of an exoplanet, and has spun a number

of follow-up observations, such as the detection of color dependencies during the transit (Deeg et al. 2001) and several attempts towards the detection of atmospheric features of the planet.

A second example has been reported very recently by Konacki et al. (2003). One of the 59 transiting candidates uncovered by OGLE in the direction of the galactic center, was found to have clear low-amplitude radial velocity changes consistent with a 0.9 Jupiter mass planet in orbit around a solar-type star. The period is only 1.21 days, making it the hottest planet known to date. The transit has a flat bottom and 1.2% depth, consistent with a Jovian-sized planet.

Transits of extrasolar planets are clearly very interesting because they nail down the inclination parameter (unknown in radial velocity surveys). High-precision photometry of large samples of stars is thus a powerful method for detecting and characterizing exoplanets. Several projects are underway, from the ground (e.g. OGLE, STARE, VULCAN, WASP) or are being planned for space missions in the same timeframe as Pan-STARRS (COROT and Kepler).

2 The role of Pan-STARRS

The sensitivity, wide-field, and fast duty cycle of Pan-STARRS can effectively be applied to the search and characterization of exoplanet transits. Current and planned dedicated surveys focus on relatively bright ($V < 12$) solar-type stars. An exoplanet Pan-STARRS survey can focus on fainter stars, which can be either more distant or less massive. We provide here two characteristic examples.

2.1 Hot Jupiters in the metal rich cluster NGC 6791

Despite being one of the oldest known open clusters (age ~ 8 Gyr, Phelps et al. 1994), NGC 6791 has the highest metallicity ($[Fe/H] = +0.4$, Chaboyer et al. 1999), and it is one of the most populous of all the open clusters. NGC 6791 is critically important for studies of the galactic age-metallicity relation and population synthesis because it is a unique and relatively nearby ($d = 3.7$ Kpc) example of the kind of old, high-metallicity population that dominates elliptical galaxies and spiral bulges.

We used the cluster luminosity function given by Kaluzny & Rucinski (1995) to estimate that there are at least 10,000 cluster members in the magnitude range $V = 17.5$ to 23.5. Even in the cluster center, the density of stars is less than 1 per arcsec sq. thus crowding is not an issue.

Using results from various radial velocity surveys, Laughlin (2000) has estimated that the rate of occurrence of hot Jupiters with $P \leq 4$ days is of order 1% among single main-sequence stars in the solar-neighborhood. However, considering only metal-rich stars ($[Fe/H] \geq 0.2$), the rate of occurrence of hot

Jupiters increases to about 10%. The chance that a hot Jupiter will produce a transit is about 10%.

Since Pan-STARRS can cover simultaneously the whole cluster, and it can observe it for several weeks, it can potentially detect most of the hot-Jupiter transits provided that the photometric accuracy is better than half a percent (see Figure 1). If hot-Jupiters in NGC 6791 are as abundant as they are around metal-rich stars in the solar-neighborhood, we expect to find about **100 transits due to jovian-sized planets**. Follow-up studies with large-telescopes will be needed to study the radial velocity curves of the stars and to obtain high-quality multicolor light curves.

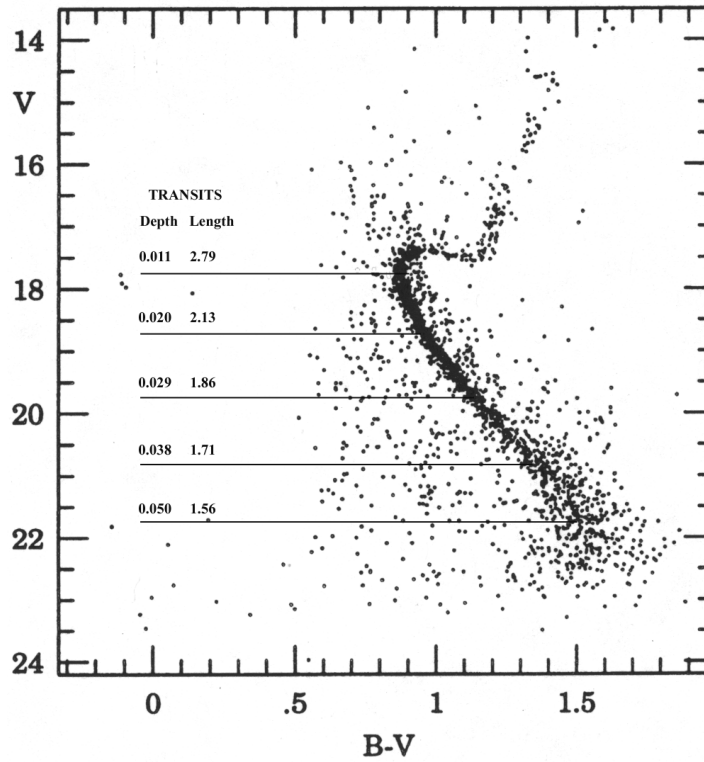


Fig. 1. Color-magnitude diagram for the central part of NGC 6791 adapted from Kaluzny & Rucinski (1995). Transit depths in magnitudes and durations in hours have been estimated for various stellar masses using the models of Chaboyer et al. (1999) and a constant planet radius of $1.3 R_{\text{Jupiter}}$.

Gilliland et al. (2000) did not find any planets in a WFPC2 survey for hot Jupiters in the globular cluster 47 Tucanae, and interpreted their null

result as evidence for a lower occurrence of planets in 47 Tucanae than in the solar-neighborhood. The cause of this difference could be the low metallicity ($[\text{Fe}/\text{H}]=-0.7$; Salaris & Weiss 1998), and/or the crowded environment in the globular cluster. NGC 6791 represents a much more favourable environment for planet formation and survival because it has about one order of magnitude higher metallicity than 47 Tucanae and it is much less crowded.

A non-detection of planets in NGC 6791 would resolve the degeneracy between metallicity and density of stars in the interpretation of Gilliland et al. (2000) results in 47 Tucanae. It would be clear then that the crowded environment (nurture), and not the chemical composition (nature), explains the lack of planets in regions with high density of stars. This would imply that the high-metallicity stars with planets in the solar neighborhood have not formed in regions with high stellar density.

On the other hand, a detection of many planetary transits in NGC 6791 would imply that metallicity is a key factor in determining the abundance of planets. It would also provide a very valuable sample of planets for which radii can be derived directly and masses can be estimated. We have estimated the transit depth and duration for stars in NGC 6791 as a function of primary mass (Figure 1). We considered a constant radius of $1.3 R_J$ for simplicity. The true radii of the planets depends on the albedo and chemical composition of the planet (Guillot et al. 1996).

2.2 Habitable planets around very low-mass stars and brown dwarfs

Very low-mass stars have sizes comparable to Jupiter, and brown dwarfs are even more compact. For example, a 0.06 solar mass brown dwarf is expected to have a radius of about 70% that of Jupiter for an age of 1 Gyr. The ratio of Jupiter/Earth radii is 9%, and the ratio of a brown dwarf to Earth is about 13%. The depth of transits scales with the ratio of the area of the primary object with respect to the secondary object. In the case of planets around brown dwarfs, a Jovian-sized object could be even slightly larger than the primary. However, we will focus here on the more challenging case of the detectability of terrestrial sized planets. The depth of the transit of an Earth-sized planet in orbit around a star with 0.1 solar masses is 0.8 %, and for a 0.06 solar mass brown dwarf primary, the depth increases to 1.6%.

The ratio of the frequency of terrestrial planet transits versus the frequency of terrestrial planets in orbit around a population of very low-mass and brown dwarfs is approximately equal to 0.006 multiplied by the number of brown dwarfs in the FOV, multiplied by the transit duration plus the duration of the observation, divided by the period of the planet to the 5/6 power. The habitability region around brown dwarfs is located at $P \sim 1$ day (Desidera 1999). For a survey that lasts much longer than the planetary period, the probability of detecting habitable planets is equal to about 0.005 times the number of objects in the FOV, multiplied by the duration of the

survey for continuous phase coverage. However, the phase coverage from one site only cannot be continuous. Therefore, the probability is approximately the duration of the survey in days divided by 400 times, multiplied by the frequency of habitable terrestrial planets around brown dwarfs, and multiplied by the number of sufficiently bright brown dwarfs in the FOV.

Pan-STARRS can cover simultaneously all the brown dwarfs in open clusters such as alpha Per or the Pleiades (about 300 for each). It can also observe hundreds of brown dwarfs in low galactic latitude fields. However, the cadence of the observations is critical. It is not good enough to have a few sparse photometric points distributed over weeks or months. Continuous time coverage is critical to improve the probability of finding transits, to improve the accuracy of the differential photometry, and to obtain the detailed shape of the light curves. As a rule of thumb, if the frequency of habitable planets around brown dwarfs is 10%, it will take approximately a 12 day survey to find one transit. In other words, a photometric survey that last a month in a region that contains 300 brown dwarfs in the Pan-STARRS FOV can either detect **a few habitable planets** or put a severe constrain on their frequency.

Spinoffs: eclipsing brown dwarfs (none known so far), activity statistics (flares, spots), rotation rates, weather patterns.

3 Survey Requirements

3.1 Filters

CCD detectors and the Earth's atmosphere are best behaved in the VR bands. Two filters are desirable to distinguish color effects. Exoplanet transits should have neutral colors, while other time variable phenomena in stars have strong color effects (cool spots, binary eclipses). For hot Jupiter transits VR are the best filters. For habitable planet transits around brown dwarfs, the I filter is necessary because brown dwarfs are very dim at shorter wavelengths.

3.2 Photometric accuracy

The depth of the transits is estimated in the range 5 to 0.8 % . Differential photometric accuracy over timescales of a few hours should be about 0.1 % , which is currently being achieved with CCD detectors on 1-meter class telescopes (Doyle et al. 2001; Everett et al. 2002).

3.3 Sky Coverage and Cadence

Exoplanet transit searches require continuous coverage of specific regions of the sky with a duration that is large compared with the orbital period of the planets that can be detected. Typical examples would be 1 month long surveys of the NGC6791 cluster in VR bands, or 1 month long survey of the Pleiades cluster in the I band.

3.4 Astrometry, Image Quality and Sky Brightness

The astrometry should be good enough for locating the objects with transits for follow-up studies (i.e. 1 arcsec). Good tracking is important to prevent the objects to drift in the detector. Sub-pixel dithering capability will improve the differential photometry. Most fields will not be very crowded. Konacki et al. (2003) have noted that many transit candidates are artifacts due to confusion of stellar sources. FWHM = 0.7 arcsec should be good enough for our purposes.

3.5 Follow Up Strategy

Planetary transits need to be detected several times to be confirmed. It should be possible to follow-up Pan-STARRS transit candidates with conventional small FOV 2-meter class telescopes. A network such as the PLANET project (follow-up of microlensing events) could be made.

Moderately precise radial velocity observations would be made to study the eclipsing binaries. Detailed multi-color light curves of confirmed transits would be made with HST and/or 4-meter class ground-based telescopes. The transits due to planets have a characteristic flat-bottom profile, while those due to grazing binaries have triangular shape (e.g. Konacki et al. 2003). The lack of large radial velocity variability, plus modelling of light curve, plus the location of the stars in the cluster sequence would provide sufficient information for determining the nature of the eclipsing objects (planets or stars).

3.6 Relation to Other Surveys

No direct competition for transits in faint objects. Other experiments are focusing on bright stars.

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