The Life Cycle of an XO Planet and the
Potential to Detect Transiting Planets of M Dwarfs

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Abstract. We describe strategies and tactics for detecting transiting planets, as learned from the experience of the XO Project. A key component is the web-enabled collaboration with a longitudinally-distributed Extended Team of dedicated volunteers operating small-aperture telescopes near their homes. We also quantify the (small) potential to discover transiting planets of M dwarfs from existing data such as that obtained by the XO Project.

1. Preface

Participants in the Workshop and the reader (we hope) generally will be aware of the many facets of detection and characterization of transiting planets. The scope of this contribution is only to describe some aspects of our incremental contributions to the art, strategies, and tactics of the particular topic of detecting transiting planets, as learned from our XO experience. Others may or may not find the tactics described here appropriate for their particular circumstances. In particular, a team with institutional access to a telescope and spectrograph and many nights of time allocated to their follow-up spectroscopy, logically could adopt tactics different from those we have adopted. Our aim has been to obtain precision multi-color photometry of transiting planet candidates to enable us to use efficiently \(~ 20\) hours allocated per year on a large telescope with an excellent spectrograph. That is, we aim to discriminate as many candidates as practical with follow-up photometry, prior to spectroscopy.

2. Life Cycle of an XO Planet

The XO Survey telescope and its operation and data analysis have been described by McCullough et al. (2005). In summary, the XO observatory monitors tens of thousands of bright (V < 12) stars twice every ten minutes on clear nights for more than 2 months per season of visibility for each particular star. XO has been operational since September 2003, and we observe each star for two seasons before moving on to new fields of view. There are two reasons for observing for more than one season: 1) to increase the probability of detection of a transiting planet, and 2) to enable multi-year precision for the extrapolation...
tion of ephemerides for follow-up observations, either precision photometry or spectroscopy.

From our analysis of more than 3000 observations per star over two seasons, we identified XO-1 as one of dozens of stars with light curves suggestive of a transiting planet. Figure 1 is an example of a “Wanted Poster” that software scripts create for each candidate for which we might consider follow-up photometry or spectroscopy. The example is XO-1, although at the time of its identification, its “Wanted Poster” was much less sophisticated than the one illustrated in Figure 1, which represents the state of the art as of September, 2006.

Here we describe those elements of the “Wanted Poster” that are not self-evident or that are critical to the method of identifying excellent candidates from the many others. Each poster is available to observers as a static image on a password-protected website, and to its creators as a human-interactive IDL widget. The upper left plot (differential magnitude versus phase) is the calibrated XO survey photometry folded with the period identified by the Box Least Squares algorithm, (BLS, Kovács et al. 2002), and below it is the unfolded version of the same photometry (w.r.t. Julian date minus 2450000). The upper right plot is the BLS spectrum with the “best” period indicated by the vertical line. Below that is the folded light curve again, but zoomed into the time around transit. In the lower left quadrant, there are three plots (a centroid plot, a fit to the light curve and a plot of $\Delta \chi^2$) and a finder chart centered on the target star from the Digital Sky Survey, DSS. The centroid plot is a scatter diagram of all centroids measured from the XO survey data. Colored points are those obtained at times predicted to be during transit. If the colored points appear significantly offset from the swarm of uncolored points, i.e. a centroid shift is evident during the transit, we suspect the candidate to be a blend of a bright star with a fainter eclipsing binary. The direction of the centroid shift vector predicts the direction of the blending star, and the vector’s magnitude approximately predicts its separation. Only rarely will such a blend be a case of a transiting planet: an example might have been HAT-P-1 (a double star of two nearly-identical stars separated by $11''$, with one star transited by a hot Jupiter; Bakos et al. 2006) observed with survey images of angular resolution of $14''$. To assist in discriminating the two cases, we reproduce a finder chart from 2MASS (lower right of “Wanted Poster”), because it has better angular resolution than the DSS, and from the 2MASS point-source catalog we estimate the faction of light (FL75 on the “Wanted Poster”) contained by the single-brightest-star within XO’s photometry aperture of $75''$ radius. From the FL75, we can reconstruct light curves to determine if a candidate is plausibly

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1 Developed in IDL by Scott Fleming, Jeff Valenti, and Christopher Burke.
2 In this case, the fit to the XO-1 light curve is awful as it does not use the B-V constraint known for the star.
3 The proceedings may not be in color.
4 The former may be intuitive but the latter counterintuitive, given the general condition that the blending eclipsing binary star’s characteristics are unknown. The key is that the depth of the dip in the combined light is small and known.
a transiting planet. Although such light curves can be studied interactively, we have also found it helpful to contour $\Delta \chi^2$ of the observations w.r.t. potential models, parameterized by the radius of the hypothetical planet (in $R_J$) and the B-V color of a main-sequence star; one such plot is below the DSS finder chart on the “Wanted Poster.” Then at a glance, a person can take the observed B-V color and its uncertainty (evident on the poster by B-V’s various forms inferred from Tycho-2, 2MASS, etc) and determine the likely range of planet radii required to match the survey photometry. Other useful facts provided on the poster are the Galactic longitude and latitude (there are more astrophysical false positives at low galactic latitudes), the length of the transit as reported by BLS (LEN) or in theory for a central-transit of a sun-like star (THYLEN), the proper motion and the Reduced Proper Motion (Gould & Morgan 2003) criterion (OK+ indicating to us that the candidate star is small enough to be consistent with a $\sim 1\%$ transit depth from a hot-Jupiter-sized planet).

Every few months, we analyzed and winnow many dozen “Wanted Posters” to a few dozen that we post on a password-protected website accessible by the XO Extended Team (ET). We generate custom ephemerides for each ET observer of all active candidates; Figure 2 is an example of such for the nights of Sep 22-25, 2006. Each candidate is assigned a grade, which represents a suggested priority for ET observations. Grades are generated initially using a sort of “Drake Equation” for a (highly nonlinear) function that is related to the probability that a candidate is a transiting planet. The Drake Equation analogy is apt, because the grade is (approximately) the product of many probabilities that are often not more than guesses, automatically generated from the facts on the “Wanted Poster.” We manually adjust grades as additional information becomes available, such as follow-up photometry or spectroscopy. Updates to the ephemerides, grades, and commentary occur as required, typically weekly.

The feedback from the ET typically is both informative and prompt. It is not uncommon for a new candidate to be rejected or increased markedly in priority within days of its initial posting to the ET. Prior to July 2006, the XO Project collaborated with the ET primarily via a website that provided data to the ET, members of which would communicate their observations via email to the Principal Investigator, who added them to the website. A significant improvement to the XO-ET collaboration was upgrading from a one-to-many website (predicated on the ET-to-PI email) that was an undesirable throttle on progress, to a Wiki website that permitted many-to-many collaboration, since the longitudinally-distributed ET collectively never stops (in principal if not quite in practice) observing, analyzing data, and collaborating. The password-protected Wiki allows ET members to upload their observations in the form of plots of light curves and associated tables of data.

The usual criteria for discriminating candidates from follow-up observations have been described by others and will not be repeated here. We can describe a few refinements that we have used and mention a few additional astrophysical false positives that we have considered, including triple and quadruple systems, potentially with eccentric orbits.

ET observations have proved very helpful in identifying gravitationally-bound triple stars. In particular, the few candidates with XO survey light curves that have photometrically-determined periods less than 24 hours have all been
rejected, to date, based upon multi-color transit light curves, expertly observed in a timely fashion by the ET. In some cases, we have verified the triple-star nature spectroscopically, via small-depth satellite spectral lines near the main (deeper) lines, or at least have verified no discernible radial velocity variation of the spectral lines, consistent with the triple-star hypothesis or a very low mass (and hence an unrealistically low density) planet. The spectroscopic signature requires a large telescope and sometimes can be difficult to discern. The signature of a triple star in a multi-color transit light curve can be observed with a small telescope and can be obvious: the “transit” depth might be 2% in R band, 1.5% in V band, and 1% in B band, for example. In some cases, multiple-star systems produce achromatic “transit” depths and shapes, and those systems require spectroscopy.
Figure 2.: Ephemerides provided to the XO Extended Team. Candidate names, and positions (altitudes and azimuths) have been redacted. The “event” column lists Egr(esses) and Ing(resses). On the web, target names are hyperlinked to the corresponding “Wanted Poster” (cf. Figure 1).

For planets with periods longer than $\sim$1 week, the orbit may not have been circularized by tidal effects. Implications of eccentricity will be analyzed elsewhere (Burke 2007, in preparation). Here we note one additional astrophysical false positive that we have imagined: an eclipsing binary system of two stars of identical effective temperature, in which the smaller star passes behind the larger star, causing the combined light to dip, but on the near-side passage, the smaller star misses transiting the larger star due to the orbital eccentricity. Such a system, improperly interpreted, can produce a negative mass for the “transiting planet” because the radial velocity curve is 180° out of phase of that expected by the transit model.

Experience has forced us to acknowledge that there will be some planet candidates for which measurement of the planet’s mass is impossible spectroscopically, not simply because the host star is too faint (e.g. Sahu et al. 2006), but even for bright stars such as the XO Project observes, because the spectral lines of the host star are very rotationally-broadened, e.g. an F dwarf with $V_{\text{sin}i} > 30 \text{ km s}^{-1}$. An upper limit might be achievable that “proves” the object’s mass is substellar, and the Rossiter effect could discriminate between 1) a triple star and 2) a transiting planet-sized object. However, the mass of the latter object...
could be unknown and (with current techniques) unknowable and yet the upper limit might not discriminate between a brown dwarf and a planet.

A metamorphosis occurs for the rare and nearly unknown star (an egg) to that of a star of intense scrutiny by many astronomers (the butterfly). Here we have described only the caterpillar phase of the life cycle. It changes markedly with two or three precision radial velocities exhibiting sinusoidal variation of $\sim0.1$ km s$^{-1}$ (McCullough et al. 2006). At that point it enters the pupa phase, involving preparation and planning for flight operations, such as on HST and SST, and for the day when its discoverers reveal it to all as a beautiful gift of Nature.

3. Potential to Detect Transiting Planets of M Dwarfs

Finding planets around M dwarfs has several scientifically rewarding benefits. Foremost, the small stellar radii and masses of M dwarfs provide sensitivity to smaller-radius planets in the case of transit searches and to lower-mass planets in the case of radial velocity searches. Also, as emphasized in the recent review by Tarter et al. (2006), a full consensus of life in the Universe would not be complete without planet statistics for M dwarfs that compromise 75% of all stars in the Galaxy. Finally, the habitable zone for M dwarfs is at small separations (0.02-0.2 AU) and periods (days, not years) improving detectability. Thus, searches for planets of M dwarfs offer great potential to study and characterize potential life-bearing planets.

In addition to the scientific benefits of M dwarf planet searches, M dwarfs offer a technical benefit to transiting planet surveys. As opposed to FGK spectral types, the M dwarfs are readily separated from giant contaminants that plague transit surveys. The radii of giants across all spectral types are too large to find transiting planets with $\sim1\%$ photometry typical for current, ground-based surveys. For a $V<11$ transit survey, only $\sim10\%$ of stars are dwarfs (Gould & Morgan 2003). Thus, separating dwarf from giant stars is imperative. In particular, photometric color-color diagrams can separate dwarfs from giants in the M dwarf regime but not well for FGK spectral types.

Another method of separation makes use of the $\sim100\times$ luminosity ratio between M giants and M dwarfs (5 magnitudes difference). For an M dwarf and an M giant of similar color and apparent magnitude, the dwarf must be much closer and consequently will have a higher proper motion than the giant assuming similar space velocity. The so-called Reduced Proper Motion diagram (Gould & Morgan 2003) is a powerful method of dwarf/giant discrimination for stars with cataloged proper motions and photometric colors, and it is particularly effective for M spectral types. The smaller brightness contrast between dwarf and giant results in a less effective separation in the reduced proper motion diagram for earlier (FGK) spectral types.

Although currently limited to the North Celestial Sphere, the Lépine & Shara (2005) proper motion catalog (LSPM) provides an excellent source of M dwarf candidates. The catalog has a limiting proper motion of $>150$ mas yr$^{-1}$ with is more than 90% complete for $|b| > 15^{\circ}$ galactic latitude down to $V<19$ mag. In addition, the catalog has been matched to the 2MASS catalog and each entry already has been verified individually by a human.
The star counts in the LSPM catalog provide an excellent means to generally characterize the properties of a transit survey necessary to detect a robust population of transiting planets around M dwarfs. Assuming the fraction of M dwarfs with a Hot Jupiter (P < 3 day) planet, \( f \sim 0.5\% \), and the probability for a Hot Jupiter to transit a M dwarf \( \sim 9\% \), imply approximately 1 transiting Hot Jupiter for every 2200 M dwarfs observed. The fraction of M dwarfs with Hot Jupiters is uncertain but tentatively is less than the fraction of FGK stars with Hot Jupiters (\( \sim 1.2\% \)) \cite{Marcy2005, Butler2004, Endl2006}. By selecting M dwarfs in the (J-H) vs. (H-K) color-color diagram from LSPM catalog, we find only 4800 M dwarfs with \( V < 14 \), 8700 M dwarfs with \( V < 15 \), and 15000 M dwarfs with \( V < 16 \). This implies at least 2, 4, and 7 transiting Hot Jupiters orbit M dwarfs with \( V < 14 \), \( V < 15 \), and \( V < 16 \), respectively in the North Celestial Sphere.

An additional caveat is relevant to the LSPM catalog. The lower limit to the proper motions in the catalog increasingly rejects luminous M dwarfs at large distances, i.e. fainter apparent magnitudes. For example, a typical local motion of 40 km s\(^{-1}\) corresponds to a maximum distance of 50 pc for the proper motion to be greater than 150 mas yr\(^{-1}\), the LSPM catalog’s lower limit. An M0 dwarf with \( M_V = 9 \) has \( V = 12 \) at a distance of 50 pc, hence for magnitudes \( V > 12 \), the catalog will begin to be increasingly incomplete for M0 dwarfs toward fainter magnitudes (i.e. an M0 dwarf is further than 50 pc and its proper motion will be less than the catalog’s limit).

Despite the advantage the faintness of M dwarfs provide in making them readily detected in proper motion catalogs, their faintness drastically hinders finding transiting planets around M dwarfs in a bright star transit survey such as XO \cite{McCullough2005}. XO transit survey is a bright star transit survey which was designed to find transiting planets around FGK stars between \( 9 < V < 12 \). The M dwarf statistics from the LSPM catalog show that the XO survey is not sensitive enough to discover more than a very few transiting planets of M dwarfs, unless the fraction of hot Jupiters (\( f \sim 0.5\% \)) around such stars has been significantly underestimated by the radial velocity surveys to date. Surveys such as XO might effectively identify transits in the case of a planet with period and phase known \textit{a priori} from a radial velocity survey, because those parameters limit the search space and consequently improve the detection sensitivity, so an M dwarf’s faintness isn’t as limiting in that case. Problems related to blending of light from additional star(s) described in Section 2 are particularly acute for (faint) M dwarfs.

A single XO strip covers 440 sq. deg. and on average contains 40 M dwarfs from the LSPM catalog down to \( V < 12.8 \) limit of XO. After calculating the blending in the photometric aperture for M dwarfs in an XO field of view only 20 M dwarfs are unblended (\( >75\% \) of the light in the aperture arises from the the M dwarf). Overall, XO currently has data available for \( \sim 200 \) M dwarfs, and after complete coverage of the North Celestial Sphere \( \sim 800 \) M dwarfs. Although not routinely analyzed for transiting planets around FGK stars, XO data down to \( V < 14 \) have sufficient accuracy to detect Jupiter radii planets around M dwarfs. We estimate further analysis of this deeper magnitude limit may provide a total of \( \sim 1600 \) M dwarfs observed by XO in the North Celestial Sphere.
From this study we conclude a transiting Hot Jupiter around a bright (V<14) M dwarf will be rare. A statistically significant sample of transiting M dwarf planets will require photometry of fainter stars (V>16) and angular resolving power than existing XO data can provide. A proper motion catalog complete to smaller proper motions than LSPM, while still maintaining the laborious human verification of proper motion and matching to 2MASS would be helpful.

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