

# LEAVITT

## A MIDEX-class Mission for Finding & Characterizing 10,000 Transiting Planets in the Solar Neighborhood

A White Paper for the Exo Planet Task Force

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## Abstract

We propose a MIDEX-class space mission with the goal to find and characterize roughly 10,000 transiting planets. When transits occur, a much more detailed characterization of the planet is possible (§1), and so a large data base of transiting planets will provide planets with a large range in periods and radii for follow-up studies. Our survey will be all-sky and focused on stars brighter than  $V=14.8$ . Down to  $V=12$ , *LEAVITT* will be able to detect Neptune-sized objects. Because of its high cadence, *LEAVITT* is about 100 times more sensitive at detecting transits than *GAIA*, while it will find more than 20 times as many transits as *KEPLER*. *LEAVITT* has multi-band photometric capability implemented via a low-res dispersive element which can obtain 0.2% (2 mmag) photometry down to  $V=14.8$ . *LEAVITT*'s high multi-band photometric accuracy reduces the number of false-positives significantly.

## 1. Introduction

Just over two hundred extra-solar giant planets (ESGPs) are currently known in 176 planetary systems<sup>1</sup> (Butler et al. 2006). Statistical analysis of these detections indicates that roughly 10% of “Sun-like” (main-sequence of type F, G & K) stars have fairly massive planets. Tabachnik & Tremaine (2002, hereafter TT2002) determined the probability density function (*PDF*) for ESGPs as a function of mass and period for the then 69 known ESGPs.. They find that 3.5% of stars have planets in the period ( $P$ ) and mass ( $M$ ) range of:  $2 \text{ days} \leq P \leq 10 \text{ years}$  and  $1 \leq M \leq 10 \text{ Jupiter masses } (M_J)$ . We use a scaled-up version (by a factor of 1.62) to account for the current, higher normalization (Sozzetti 2005). Note that the TT2002 *PDF* ( $PDF_{ESGP}$ ) diverges for large periods *and* small masses, so that it is likely that the  $PDF_{ESGP}$  turns over at both low masses and long periods. The extrapolation of the TT2002 *PDF* to Uranus/Neptune masses increases the numbers by a factor of 2.6, and we find that 16% of stars should have planets in the range  $2 \text{ days} \leq P \leq 10 \text{ years}$  and  $0.05 \leq M \leq 13 M_J$ . Extrapolating to Earth-mass planets and up to the period of Neptune, the state-of-the art  $PDF_{ESGP}$  predicts planets around two out of three stars.

In two related proposals, we propose to explore two extremes of the *PDF*: 1) long-period massive planets (“Finding Solar System Analogs With SIM and HIPPARCOS”) and 2) Earth-mass planets in the habitable zone (“Hunting for Earth-Mass Extra-Solar Planets with the Dispersed Fourier Transform Spectrometer”). Here we propose a MIDEX-class, space-based survey aimed at finding and characterizing about 10,000 transiting planets. Finding transiting planets is not so difficult as they periodically dim the light of their parent stars substantially (at the 1% level). However, *knowing* that an observed dimming is due to the transit of a planet rather than to myriad other possible effects (false-positives), that

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<sup>1</sup> <http://vo.obspm.fr/exoplanetes/encyclo/encycl.html> and <http://exoplanets.org/>

is the hard part. In fact, it is thought that the false-positives outnumber planetary transits (PTs) by about a factor of one hundred. We will circumvent this problem to a large degree by looking at bright sources to avoid confusion, and by obtaining simultaneous multi-color photometry at the milli-magnitude level. See §3.1 below for a detailed description of our mission concept and implementation.

In contrast to radial-velocity (RV) of astrometric surveys, a transit survey will not yield the masses of the planets, but the otherwise inaccessible planetary radius. Since the masses can be determined via RV follow up (and the known inclination from the transits), our proposed survey would provide the mean density for a large number of extra-solar planets. Also, these planets allow for the search for and detection of planetary atmospheres via transmission spectroscopy (Charbonneau et al. 2002) while the combination of on- and off transit spectroscopy can also yield the continuum [e.g., Deming et al. (2006); Charbonneau et al. (2005)] and emission spectra (Richardson et al. 2007; Grillmair et al. 2007). Both detections and non-detections of continuum and spectral features in the spectra of ESGPs lead to improved knowledge of their atmospheric properties such as temperature, albedo, dust contents, cloud cover, heat redistribution, weather and so forth [e.g., Richardson et al. (2007); Seager et al. (2005); Fortney et al. (2003); Menou et al. (2003); Brown et al. (2002)]. Also, eclipse-timing techniques (Irwin 1959) can be used to search for additional (down-to Earth-mass) planets [e.g., Agol & Steffen (2007); Agol et al. (2005); Steffen & Agol (2005); Miralda-Escudé (2002)] in the most suitable systems.

Thus, to quote Charbonneau et al. (2007), “When extrasolar planets ... transit their parent stars, we are granted unprecedented access to their physical properties.” In fact, spectroscopy of extra-solar planets could eventually lead to the detection of life on another planet [e.g., Turnbull et al. (2006); Tinetti (2006); Seager & Ford (2005); Des Marais et al. (2002)], which is of course the goal of NASA’s *TPF* missions<sup>2</sup> and ESA’s *DARWIN*<sup>3</sup> project.

Finally, it has been long presumed that the migration of giant planets towards close-in orbits would destroy the proto-planetary disk and would thus inhibit the formation of additional planets. However, the most recent simulations indicate that while the migration temporarily destroys the accretion process, the formation of earth-mass planets goes on in about 60% of the models studied by Fogg & Nelson (2007, 2005) and Mandell et al. (2007). This perhaps surprising result can be explained by the fact that giant-planet formation+migration occurs very rapidly, as compared to the formation of terrestrial planets. As a result, the “perturbation” due to migration is minor. These results indicate that our proposed survey of transiting planets would also yield a catalog of systems that would be

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<sup>2</sup> [http://planetquest.jpl.nasa.gov/TPF/tpf\\_index.cfm](http://planetquest.jpl.nasa.gov/TPF/tpf_index.cfm)

<sup>3</sup> <http://sci.esa.int/science-e/www/area/index.cfm?fareaid=28>

enriched with earth-mass planets (with respect to blind searches).

## 2. Transit Surveys

There is a large number of on-going ground-based transit surveys inspired by the apparent ease of detecting the  $\sim 1\%$  transit signal [e.g., Horne (2003)]. However, the results have been at least an order of magnitude smaller than expected. To quote Pont et al. (2006), “... Altogether, thousands of [1–4 m] telescope nights have been invested in these surveys, monitoring hundreds of thousands of target stars in the solar neighborhood and in the Galactic disc. However, even after years of operation, the results of these surveys failed to meet the expectations, with only a slow trickle of detections instead of the expected bounty. ...” end quote. Pont et al. (2006) argue that this is due to correlated noise on time-scales of several hours that are due to, for example, atmospheric effects, temperature, and tracking errors vary on roughly the same time-scale of several hours: the duration of the transit (Pont *et al.* 2006). In fact, it is (or should have been) rather well known that milli-magnitude photometry is rather difficult to achieve from the ground. This is exactly the reason why *HIPPARCOS* (ESA 1997) photometry is the best available, and why *GAIA*<sup>4</sup> spends so much of its focal plane of photometry (and spectroscopy). For example, the extremely well-calibrated *SDSS* survey achieves roughly 1% ( $\sim 10$  mmag) relative photometry Padmanabhan et al. (2007).

## 3. Mission Concept

On the other hand, as stated above, photometry at the mmag level is much more easily achieved with space-based platforms. However, note that for example *HST* photometry is not that accurate. To achieve this goal, one must repeatedly observe the same star many times, while it is also crucial to have excellent knowledge of the point-spread function (PSF). The former criterion is required so as to be able to remove long-term trend, eliminate instrument-related systematics etc.. In other words, demand consistency. Knowledge of the PSF is crucial because (in crowded fields) PSF-fitting yields superior integrated magnitudes. If a mismatch exists between actual PSF and assumed PSF, systematic effects will creep in the photometry. For this reason, astrometric programs are well-suited to obtain very accurate photometry, because they too need many repeat measurements and exquisite PSF control/knowledge such as in *HIPPARCOS*, *GAIA* (Perryman 2005) and the canceled *FAME* project (Johnston 2003) and the proposed *AMEX* (Gaume 2005; Gaume et al. 2003) and *OBSS* missions (Johnston et al. 2006).

### 3.1. The MIDEX-Class LEAVITT Mission

Based on our extensive experience with proposed the *FAME*, *AMEX* and *OBSS* astrometric missions, and their transit capabilities in particular [e.g., (Olling 2003; Olling & Gaume

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<sup>4</sup> <http://gaia.esa.int/science-e/www/area/index.cfm?fareaid=26>

2002; Gaume & Olling 2002)], we propose the following *LEAVITT*<sup>5</sup> MIDEX-class space mission.

The basic property a transit survey needs to have is a rapid cadence, therefore, *LEAVITT* will spin every 90 minutes. A “precession period” of 15 days ensures that 70% of the sky is observed about once every week (the remaining 30% is inaccessible due to the Sun exclusion zone). In total, the number of observations will be 10,500 in 5 years.

So as to keep the mission with the 159 M\$ MIDEX budget, we propose a (cheap) Sun-synchronous Polar orbit such as those of IRAS, COROT<sup>6</sup> and many others. Like the scanning astrometric missions, *LEAVITT* would have two viewports separated by a basic angle of  $\sim 90^\circ$  that project the light onto the same focal plane. However, significant cost reductions are achieved because we are dealing with a photometric mission, so that we do not require the exquisite basic angle stability as required by *LEAVITT*'s astrometric cousins. The mirror is rectangular and measures 14x55 cm with a focal length of 5 meters.

The instantaneous field of view is  $3.5^\circ \times 3.5^\circ$ , which is covered by 36 CCD (5,120 x 5,120 with  $10 \mu$  pixels (similar to *OBSS*) that operate in drift-scan mode (like SDSS and *GAIA*, etc.). The wide field of view ensures that a given stars is observed regularly for about 6.6 hours before the scanned strip moves off target. Typically, this period (epoch) is long enough to cover a planet transiting its parent (2 to 3 hours), as well as have baseline observations outside transit.

A crucial aspect of the instrument is the inclusion of a dispersive element that creates rather low-res ( $R \sim 100$ ) slitless “spectra” for each object. These spectra are required for two reasons: 1) it extends the dynamic range of the instrument by roughly 5 magnitudes, and 2) it provides highly accurate color information that is crucial for the characterization of the transit event, and hence reduce the false-alarm rate to manageable levels. Tingley (2004) shows that color changes during transit are at the 1 mmag level, while false-positive are several times larger. Other, color-independent methods can also be used to reduce the false-alarm rate [e.g., (Tingley & Sackett 2005; Seager & Mallén-Ornelas 2003)]. Our usable magnitude range is 5.7 (saturation) to 14.8 (2 mmag photometry for 3-color photometry per hour integration time).

The moderate dispersion can be achieved by a low-power dispersive element prism in the light-path (such as was planned by *DIVA*<sup>7</sup> or *COROT*, or ESO's WIFI imager)

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<sup>5</sup> We propose this project in honor of Henrietta Swan Leavitt who contributed very significantly to precision astrophysics with the discovery of Cepheid variables in the Magellanic Clouds almost one hundred years ago, and opened up the field of temporal astrophysics. Alternatively, LEAVITT could stand for: “LEgacy Astrophysics of Variable, Intermittent and Transiting Things.”

<sup>6</sup> <http://smc.cnes.fr/COROT/>

<sup>7</sup><http://www.ari.uni-heidelberg.de/diva/>

The above strategy implies that *LEAVITT* will visit the average star  $\sim 168$  times in 5 years, while  $\sim 61$  observations are taken during those 168 6.6-hour epochs.

We simulated the expected number of transits in the following manner: 1) we perform a full-length mission simulation that measures the number of visits at arbitrary points on the sky, 2) these data are then used to determine a sky-averaged probability for detecting *five* transit-like events with a duration determined by the period of the planet (transits last longer in longer-period orbits), 3) here we assume a G2V primary and a planet with Jupiter’s radius, 4) we use the modified TT2002 *PDF*, multiplied this by the probability that the planet is seen edge-on, and the probability of observing 5 transits as determined in (2) above, 5) we use a simple star-count model of the solar neighborhood to predict how many dwarf stars are with our magnitude limit, and 6) generate the total number of observable planetary transits.

The combined effects of *LEAVITT* not observing continuously, and the period distribution of the ESGPs indicates that *LEAVITT* is  $\gtrsim 50\%$  complete for periods shorter than 18 days. This compares very well with 2.4 days for *GAIA* (for which we performed the same simulations). In fact, *LEAVITT* outperforms *GAIA* by a factor of 100 (460) at a period of 10 (20) days. This is mostly due to *GAIA*’s very slow precession rate of 75 days. *LEAVITT* will produce roughly 20 times more PTs than *KEPLER*. On the other hand, *KEPLER* can find planets with a radius of the Earth at  $V = 12$ , while *LEAVITT* can detect Neptune-size objects at that magnitude.

If we assume planets down to Uranus/Neptune mass, we expect to find roughly 21,000 planetary transits with periods roughly up-to 30 days. The brightest subset of  $\sim 10,000$  planets will have 3-color photometry at the 2 mmag level, and these are the systems that can most likely be classified photometrically as transiting planets.

### 3.2. Cost Estimate

We compared our *LEAVITT* mission with the *FAME*, *AMEX* and *OBSS* missions to arrive at a reasonable cost estimate. Our cost model takes into account the overall weight, launch costs, mirror size, number of CCDs, electronics, instrument weight, bus mass, attitude control and science operations. We define scaling relations that result in good estimates for the *FAME*, *AMEX* and *OBSS* budgets. This model results in a total cost for the *LEAVITT* mission of 159 M\$ (FY2005).

## REFERENCES

- Agol, E., & Steffen, J. H. 2007, MNRAS, 374, 941  
 Agol, E., Steffen, J., Sari, R., & Clarkson, W. 2005, MNRAS, 359, 567  
 Brown, T. M., Libbrecht, K. G., & Charbonneau, D. 2002, PASP, 114, 826  
 Butler, R. P., et al. 2006, ApJ, 646, 505  
 Charbonneau, D., *et al.*, 2007, Protostars and Planets V, 701

- Charbonneau, D., et al. 2005, ApJ, 626, 523
- Charbonneau, D., *et al.*, 2002, ApJ, 568, 377
- Deming, D., Harrington, J., Seager, S., & Richardson, L. J. 2006, ApJ, 644, 560
- Des Marais, D. J., et al. 2002, Astrobiology, 2, 153
- ESA, 1997, The Hipparcos and Tycho Catalogues, ESA Publication Division
- Fogg, M. J., & Nelson, R. P. 2007, A&A, 461, 1195
- Fogg, M. J., & Nelson, R. P. 2005, A&A, 441, 791
- Ford, E. B., 2006, PASP, 118, 364
- Fortney, J. J., *et al.*, 2003, ApJ, 589, 615
- Gaume, R. A. 2005, ASP Conf. Ser. 338, 53
- Gaume, R. A., Johnston, K. J., & AMEX Program Team 2003, BAAS, 35, 1206
- Gaume, R. A., & Olling, R. P. 2002, BAAS, 34, 1165
- Grillmair, C. J., *et al.*, 2007, ApJ, 658, L115
- Horne, K. 2003, ASP Conf. Ser. 294, 361
- Irwin, J. B. 1959, AJ, 64, 149
- Johnston, K. J., et al. 2006, PASP, 118, 1428
- Johnston, K. J. 2003, SPIE, 4854, 303
- Mandell, A. M., Raymond, S. N., & Sigurdsson, S. 2007, arXiv:astro-ph/0701048
- Miralda-Escudé, J. 2002, ApJ, 564, 1019
- Menou, K., Cho, J. Y.-K., Seager, S., & Hansen, B. M. S. 2003, ApJ, 587, L113
- Olling, R. P., 2003, e.g., several technical memoranda located at:  
<http://www.astro.umd.edu/~olling/FAME/XXX>, where XXX can be one of the following: Astrometry\_Stars\_Galaxies\_Universe.pdf, ftm2003\_02.pdf, ftm2003\_01.pdf, Astrometry\_SMEX\_MIDEX\_DISCOVERY.pdf, FTM2001-15.pdf, FTM2001-07.pdf, FTM2001-03.pdf
- Olling, R. P., & Gaume, R. A. 2002, BAAS, 34, 1165
- Padmanabhan, N., et al. 2007, arXiv:astro-ph/0703454
- Perryman, M. A. C. 2005, ASP Conf. Ser. 338,3
- Pont, F., Zucker, S., & Queloz, D. 2006, MNRAS, 373, 231
- Pont, F., & the ISSI Working Group on Transiting Planets 2006, arXiv:astro-ph/0612540
- Richardson, L. J., *et al.*, 2007, Nature, 445, 892
- Seager, S., & Ford, E. B. 2005, Astrophysics of Life, 67
- Seager, S., *et al.*, 2005, ApJ, 632, 1122
- Seager, S., & Mallén-Ornelas, G. 2003, ApJ, 585, 1038
- Schneider, J, 23 July 2006 The Extra-Solar Planet Encyclopedia  
<http://vo.obspm.fr/exoplanetes/encyclo/encycl.html>
- Sozzetti, A. 2005, PASP, 117, 1021
- Sozzetti, A., Casertano, S., Brown, R. A., & Lattanzi, M. G. 2003, PASP, 115, 1072
- Steffen, J. H., & Agol, E. 2005, MNRAS, 364, L96

- Tabachnik, S., & Tremaine, S. 2002, MNRAS, 335, 151  
Tinetti, G. 2006, Origins of Life and Evolution of the Biosphere, 36, 541  
Tingley, B., & Sackett, P. D. 2005, ApJ, 627, 1011  
Tingley, B. 2004, A&A, 425, 1125  
Turnbull, M. C., *et al.*, 2006, ApJ, 644, 551