# GROUND-BASED CHARACTERIZATION OF THE *EDDINGTON* PLANET FINDING FIELD

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## Abstract

In this paper we discuss the observations needed for the ground-based characterization of the *Eddington* Planet Find Field (EPFF). Ground-based characterization is necessary in order to successfully plan the observations of *Eddington*. The limited telemetry available from the spacecraft imposes an a priori selection of the targets to be photometrically monitored. An appropriate characterization allows to define the optimal temporal sampling of the targets for the planet transit search, and to identify targets for asteroseismology and parallel science studies. The amount of ground-based data to be collected, and the corresponding huge amount of reduction and analysis work, imposes an immediate start of the characterization program.

## 1. Introduction

One of two main scientific objectives of *Eddington* is the detection of extrasolar planets in habitable zones using the photometric transit technique. A three year continuous observation of a $\simeq$ 17 square degree field will allow monitoring up to a hundred thousands stars to search for transits. Only a fraction of the stars in the *Eddington* Planet Find Field (EPFF) will be useful for the detection of terrestrial planet transits. Evolved giants must be excluded because their radii are too large to allow identifying the passage of a planet in front of their disk; they also typically show intrinsic photometric variability. Early type stars are also not interesting targets for the main *Eddington* science goal, though transiting giant planets might still be detectable on them. The best targets for the detection of Earth-mass planets (which is the primary objective of *Eddington*) are late F, G, K, and M dwarfs.

The photon collection capability of the *Eddington* telescopes allows to search for planets in the habitable zone down to $V \simeq 14$ (Favata 2003), while giant planets will be accessible down to much fainter magnitudes ($V \simeq 17$). As shown in our work (cf. Barbieri et al. 2003), we expect more than 200 000 stars with $V < 17$ in the optimal EPFF. Due to the limited available telemetry (130 kb/s), it is impossible to transfer the full CCD mosaic images to ground; it is also impossible to perform and transmit the photometry at the full CCD readout cadence (8 sec) for all the stars in the EPFF. Some target selection as well as rebinning of the time series for the selected targets will be needed in order to maximize the number of stars which can be monitored. Current plans (Catala 2002) foresee a 4 time binning (of the single 8 sec exposures), with a resulting sampling time of 32 s for stars brighter than $V = 15$ (up to 20 000 stars), and a 75× time binning of the single exposures, with a resulting sampling time of 600 s, for stars with $15 < V < 17$ (about 80 000 stars). For a limited ($\simeq$ 100) sample of particularly interesting targets it will be possible to have the actual (stacked) images from a small CCD window around each one of them.

This complex observing plan, and the impossibility to download the CCD images, makes an accurate ground-based characterization of the selected EPFF of paramount importance. Multiband wide field broad band and intermediate band imaging, and low resolution spectroscopy is needed not only to identify the appropriate target stars, but also to optimize the temporal sampling of each target.

In the long duration planet-finding observing field, the photometric accuracy and the time sampling will give photometric time series of unprecedented high accuracy that will allow asteroseismology studies of stars in different regions of the color-magnitude diagram. An appropriate characterization of the EPFF will also allow to select good candidates for asteroseismology studies.

The definition of the observing strategy will depend on the EPFF characterization. In this paper we briefly outline which kind of ground-based data are needed for an appropriate characterization of the EPFF. The actual strategy to be followed will depend on the amount of financial and human resources available.

## 2. Ground-based characterization

The first goal of the observations for the characterization of the EPFF is the identification of the highest number of late F, G, K, and M dwarfs. A more detailed measurement of their parameters (like variability, proper motion, metal content, etc.) would further help to optimize the observing strategy.

The minimum set of observations necessary for the ground-based characterization of the EPFF is:

1. Multiband (*UBVRI*) wide field broad band photometry of the entire EPFF.

Proc. 2nd *Eddington* workshop *"Stellar Structure and Habitable Planet Finding"*, Palermo, 9–11 April 2003 (ESA SP-538, January 2004, F. Favata, S. Aigrain eds.)

2. Extraction of near-IR photometry from the 2MASS catalog. More accurate near-IR photometry is highly recommended, and eventually needed for the fainter targets.
3. A further selection of appropriate candidates for planet finding can be done with intermediate band photometry, like Strömgren, or Washington photometry, or some specific intermediate band photometric system designed for a more accurate estimate of effective temperatures, gravities, surface metallicity, and reddening.
4. Low resolution spectroscopy for the stars selected on the basis of the wide field broad and intermediate band photometric data.
5. Variable star identification and proper motion measurements are also advisable.

### 2.1. Wide field broad band photometry

Multicolor broad band (e.g. *UBVRI*) photometry is mandatory during the mission preparation phase in order to have magnitudes, colors, and accurate stellar positions. Stellar magnitudes and colors are needed in order to apply a first selection on the few hundred thousand stars present in the EPFF. In general magnitudes and accurate positions are needed in order to define the stellar masks for the onboard aperture photometry measurements.

The size of the EPFF necessarily imposes the use of wide field imaging (WFI) facilities. Appropriate facilities are available both in the northern (e.g. CFH MegaCam, and the wide field imager at the INT) and southern (ESO WFI@2.2, and OmegaCam at VST, when ready) emispheres.

Figures 1 and 2 show the color-magnitude diagrams (CMD) from broad band photometry in two Galactic fields at $(l, b) = (329, -3), (260, +7)$ respectively, from the ESO WFI@2.2m telescope. These two plots clearly show that down to $V = 15$ it is easily possible to eliminate most of the evolved giants using color-magnitude diagrams. In this way, we will eliminate also a number M dwarfs, but we expect to find very few of them in this magnitude interval. A color selection on the blue edge allows also to eliminated early type, non reddened stars. Below $V = 15$, some confusion arises, and it becomes more and more difficult to distinguish between evolved giants and late type dwarfs, particularly if we consider K and M dwarfs, which are rather good targets for the search of planets in habitable zones (Gould et al. 2003, Deeg 2003). The remaining stars are a mixture of early type reddened stars in the background and late type dwarfs. We need further observations to identify the latter.

There are a number of wide field imaging facilities which can be used to obtain broad band (and, in principle, also intermediate band) photometry. In the Southern hemisphere we can use the ESO WFI@2.2m camera. The camera covers a field of approximately 30 × 30 arcmin square. The continuous monitoring region of the EPFF

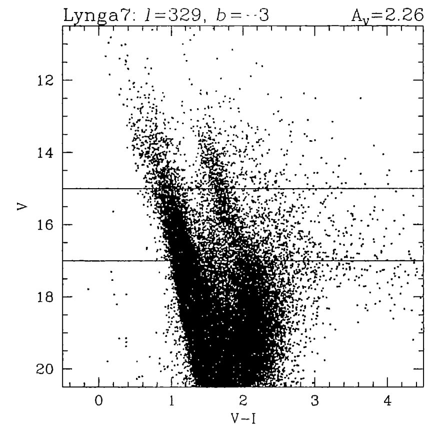


*Figure 1. V vs. $V - I$ color-magnitude diagram (CMD) of a $34 \times 33$ arcmin$^2$ field in the direction of the Galactic globular cluster Lynga 7. The tiny cluster occupies the very inner region of the observed field. The reddening in front of the cluster is $E(B - V) = 0.7$. This CMD can be representative of a typical Galactic field located at $l = 328, b = -3$.*

will be a circular region covering an area $\simeq 20$ deg square in area, which can be covered with 100 WFI@2.2 fields. Each field can be covered with $(3 \times 5)$ exposures (3 exposures to fill the CCD mosaic gaps, and 5 bands). In order to reach $S/N = 100$ at $V = 17$, we need exposures of 90, 10, 10, 10, 10 s in *UBVRI* respectively, for a total of 50 hours of actual photon collection time, to which we need to add $100 \times 3 \times 5 \times 2$ min, i.e. 50 hours of overheads. Overall, the EPFF could be mapped with WFI@2.2 in about 10 nights. The same job would be carried out in less than 3 nights with OmegaCam at VST and MegaCam at CFH, and in about 10 nights with the Isaac Newton Telescope wide field imager. Broad band photometry characterization does not require a huge amount of telescope time. However, it must be noted that 1500 images will be collected, for a total of almost 400 Gb of (raw!) data, which immediately double in size after flat fielding. Accurate photometry and astrometry must be obtained for many hundred thousand stars. It is not a telescope consuming job, but it requires a large amount of disk space, and, more important, at least one year of work of a (trained) post doc, full time dedicated to the job.

### 2.2. Near-IR photometry

The large wavelenght baseline obtained combining broad band optical data with near-IR photometry allows to better discriminate evolved late type giants from dwarfs, even below $V = 15$. Moreover, combining multiband photometry from $B$ to $K$ bands allows to estimate the reddening of single stars (e.g. Romaniello et al. 2002), enabling to

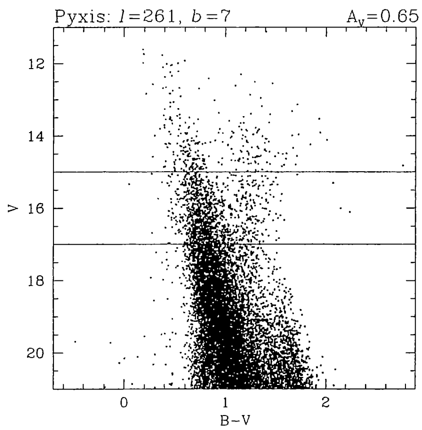


*Figure 2. V vs. B − V color-magnitude diagram (CMD) of a 34 × 33 arcmin² field in the direction of the Galactic globular cluster Pyxis. The tiny cluster occupy the very inner region of the observed field. The reddening in front of the cluster is $E(B-V) = 0.2$. This CMD can be representative of a typical Galactic field located at $l = 361, b = 7$.*

eliminate some of the early type, reddened stars in the EPFF.

The easiest approach which can be adopted for the characterization of the EPFF is to combine the WFI broad band optical data with the 2-MASS data.

More accurate near-IR photometry of the EPFF should be taken into account, at the UKIRT (for the northern hemisphere) or VISTA (when it will become available, and for the southern hemisphere)

### 2.3. Intermediate band photometry

Intermediate band photometry, like the Strömgren *ubvyβ* photometric system, or the Washington or DDO systems complement the broad band photometry, and offers additional advantages, allowing a more precise estimate of the effective temperature, gravity, and reddening. A huge effort devoted to the calibration of photometric indexes from these systems as a function of the stellar parameters is present in the literature (see e.g. Crawford 1975, Olsen 1984, Schuster & Nissen 1989, Martell & Laughlin 2002 for Strömgren photometry, and Majewski et al. 2000 for DDO photometry). It might be also useful to think about some intermediate/narrow band photometric system, specifically defined to identify the late type stars which are ideal targets for the habitable planet search. In this case, additional calibrating work must be taken into account.

Though it seems unavoidable that some intermediate band photometry must be carried out to identify the needed late type dwarfs in the magnitude range $15 < V < 17$, the main problem seems that no complete filter sets for the photometric systems already defined and calibrated is presently available (or foreseen) at the wide field image observing facilities, so that they must likely be procured. A filter for OmegaCam at VST can cost up to 50 KEur, depending on the adopted technical solution (single large, more expensive filter, or a set of four smaller filters).

The required telescope time to collect the data (e.g. in the complete Strömgren photometric system) for the EPFF size is again of the order of 10 nights at the WFI@2.2 and INT telescope, and 3 nights with the OmegaCam at VST ot MegaCam at CFH. The amount of data (in terms of number of images, and image size) is the same as for the broad band photometry. It might be more complicate (and more time demanding) to calibrate the data.

### 2.4. Low resolution spectroscopy

An alternative to intermediate band photometry for stars with $V < 15$ is low resolution spectroscopy, which allows spectral classification. The optimal resolution for spectral classification is about 2 Å ($2000 < R < 4000$), but also spectra with resolution down to $R = 500$ and broad spectral coverage provide reliable results (Torres-Dodgen and Weaver 1993).

As fully described in Barbieri et al. 2003, we used the so called HRD–GST, i.e., the Hertzsprung-Russell diagram Galactic Software Telescope by Ng (1994) and Ng et al. (1996) in order to simulate the color magnitude diagrams and star counts in selected Galactic fields. For any reasonable field selection, for $V < 15$ the number of early type dwarfs plus evolved giants ranger from approximately equal to approximately twice the number of late type dwarfs that *Eddington* shall observe with the the highest $S/N$ (cf. Barbieri et al. 2003). Selecting for color in the color magnitude diagram (Figs. 1 and 2), we can eliminate at most half of the unwanted stars, i.e. all the evolved stars. Also part of the early type dwarfs can be eliminated with a color selection. Still, we need to distinguish between early type, reddened, main sequence stars in the background from the dwarfs of spectral type F and later. If we want 20 .000 late type dwarfs, we might need to eliminate up to 20 000 giants, depending on the Galactic latitude, so that, for an optimal characterization, we need spectral and luminosity class classification for some 40 .000 stars with $V < 15$.

There are a number of facilities, especially in the southern hemisphere (e.g., 2dF or 6dF) which allows to collect the needed observation in a reasonable amount of telescope time (15 to 20 nights). Still, the reduction of such a huge number of spectra, and the classification of the corresponding stars requires a considerable investment in human resources.

It does not seem feasible to use low resolution spectroscopy spectra to select the *Eddington* targets much fainter than $V = 15$. For these stars, intermediate band photometry is the only solution, though providing less accurate spectral and luminosity class classification.

### 2.5. Proper motions

Proper motion measurements might be an alternative way to select late type dwarf candidates for the *Eddington* photometric monitoring, even below $V = 15$. As shown by Gould and Morgan (2003), the reduced proper motion technique seems to be very effective in selecting nearby late type dwarfs. The basic idea is that, on average, background bright giants or reddened early type main sequence stars have much lower reduced proper motions than dwarfs at the same color. In order to make the technique work, we need both accurate photometry and proper motions. Available photometric and astrometric catalogs do not allow the use of this technique for stars fainter than $V = 12.5$ (Gould and Morgan 2003). On the other hand, as discussed in the previous sections, it is relatively easy to get very accurate, broad band photometry down to $V = 17$ for the stars in the selected EPFF. The measurement of proper motions is much more difficult and time consuming. We need to have proper motion errors which are significantly smaller than the measured proper motion in order to efficiently use the reduce proper motion technique. Using Eq. 3 of Gould and Morgan (2003), we expect that a star with $r = 1.25 r_\odot$ ($M_V = +4$) has on average a proper motion $\mu \sim 5$ mas/yr at $V = 15$, which decreases to $\mu \sim 3$ mas/yr at $V = 16$. K and M dwarfs should have incresingly larger proper motion at a given magnitude than late F, G dwarfs, making their identification easier.

In Padova, we are working on the possibility to extract high accuracy proper motions from ESO WFI@2.2 images. At the present time (Fig. 3), we can reach (in the central field of WFI@2.2) with two sets of 15 images, separated by 4 years, we reach $\sigma_\mu = 1$ mas/yr, accurate enough to allow the use of the reduced proper motion technique to select G dwarfs down to at least $V = 15$ (and fainter, eventually down to $V = 16$, though with an increasing contamination by background bright stars). The relatively larger proper motion of K and M dwarfs should allow to select them with the reduced proper motion technique down the *Eddington* magnitude limit.

The main challenge is to extend these astrometric capabilities to the entire $30 \times 30$ arcmin$^2$ field of the WFI@2.2 camera. We are working on this project, in view also of the potential applications for the characterization of the EPFF.

### 2.6. Variability

Variability with a photometric accuracy unreachable with ground-based photometry will be obtained directly from the photometric sequences collected by *Eddington.* Multi epoch photometry to identify variable stars is surely useful for cleaning the catalog from stars unsuitable for the planet transit search. It is also useful for the identification of interesting targets for asteroseismology and parallel science in order to maximize the scientific output of the *Eddington* mission. Still, it must be decided at which level of photometric accuracy we should look for variables with ground-based observations. Variability characterization can be very expensive in terms of telescope, hardware, and human resources.

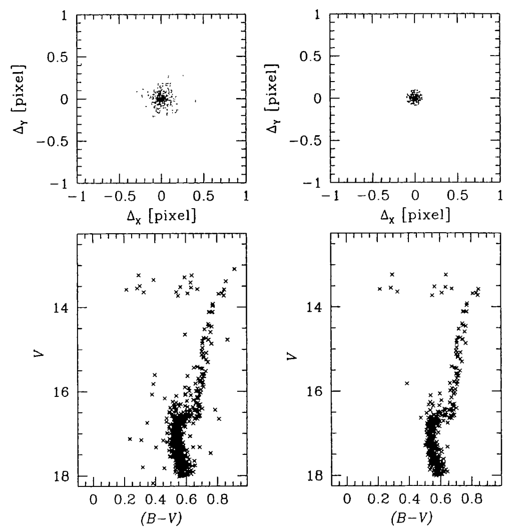


*Figure 3. Positional displacement with a 2.8 yr time baseline (top panels) and color-magnitude diagrams (bottom panels) for a stellar cluster obtained from the overlapped region of the chips. The left hand plots are for all stars in the field of view, the right hand ones for cluster stars selected by the proper-motion criterion. 1 WFI@2.2m pixel = 238 mas.*

### 3. Conclusions

Pre-launch, ground-based characterization of the EPFF is mandatory for planning a successful mission. Characterization is needed to identify the best targets for the planet search, and for the definition of the time sampling of the photometric curves for each target. Characterization is also needed for the identification of interesting targets for asteroseismology and parallel science studies.

The minimum requirement are multiwavelength broad band observations with wide field imagers in order to obtain the magnitude and position of the stars in the EPFF, and in order to apply a first selection of the useful targets for the planet search.

Low resolution spectroscopy can be used to further select the late type dwarfs down to $V \simeq 15$. Also intermediate band photometry in Strömgren, or Washington, or

DDO system, or using some filters designed for the specific purpose of selecting F and later spectral type dwarfs is needed. Intermediate band photometry allows a less effective selection of useful dwarfs than low resolution spectroscopy, but it can be used down to $V = 17$.

Finally, proper motion measurements could be very useful to select the targets for the planet search. Current technique seems to allow the needed accuracy in proper motion measurements down to $V \sim 16$ in wide field images.

A final comment is needed. Ground-based characterization does not require an inordinate amount of observing time, particularly if we can use wide field cameras like the OmegaCam (or MegaCam) and multi-fiber spectrographs, like 2dF or 6dF. However, the amount of collected data is huge, and the reduction and analysis of the observations require a lot of human resources and time. It may sound obvious, but we need to state it explicitly: *in order to have the catalog of targets for the planet search ready for the launch of the satellite, we need to start immediately the groundbased characterization of the EPFF.*

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