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RATS: Italian project fore exoplanets transit search

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Abstract. The RATS (RAdial velocity and Transit Search) project is a collaboration among INAF sections of Catania, Napoli, Padova and Palermo the Physics and Astronomy departments of Padua University and ESA. The main goal of the project is to discover at least 10 news planets transiting the host star. We also report on the characteristics and the performances of the CCD cameras that will be used by the project. We describe the characterization measurements done in laboratory and the first tests at the Asiago Schmidt telescope at Cima Ekar. Finally, we present the concept of an IRAF-based automatic data-reduction pipeline for RATS.

Key words. Stars: planetary systems – Techniques: photometry

1. Introduction

Since 1995, when the Jupiter-like planet 51 Peg b Mayor & Queloz (1995) was discovered, identification and study of extrasolar planets are between the main goals of the international astronomical community. Up to day 166 planetary systems (20 are multiple systems) for a total number of 206 planets are listed in the Extrasolar Planets Encyclopedia (vo.obspm.fr/exoplanetes/encyclo/catalog.php). Most of these planets have been discovered using the radial velocity method however a small fraction of them have been detected thanks to their transit in front of the host star. The detection of transit allows to unveil information that cannot be obtained through the radial velocity analysis. On the other hand the analysis of the transit curve yields almost directly information on the radius, the mass and hence the density of the planet. Unfortunately the geometric probability of a transit is generally low depending on the ratio $R_\star/a$ between the stellar radius and the major semiaxis of the orbit. This means that to have a high probability of detecting a transit one has to sample a large number of stars. Furthermore the photometric accuracy of the observations has to be of the order of < 0.01 mag for giant planets transiting a solar type stars and much less < 0.0001 for earth-sized

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planets. While the first figure is generally achievable using ground based instruments the second one can be obtained only from space. Temporal coverage is one more issue... Last but not least there are several phenomena that can mimic a planetary transit, e.g. eclipsing M dwarves, grazing eclipses, etc. This means that to disentangle these other effects each candidate transiting planet has to be observed spectroscopically. The RATS project is a collaboration among the INAF sections of Catania, Napoli, Padova and Palermo the Physics and Astronomy Departments of Padua University and ESA whose main goal is the discovery of giant planets transiting solar type stars. The project will have a duration of five years during which the detection of at least ten new extrasolar planets is expected. Another important goal of the project is to test the strategy of observation, data reduction and archiving of the ESA future missions for exoplanets searches.

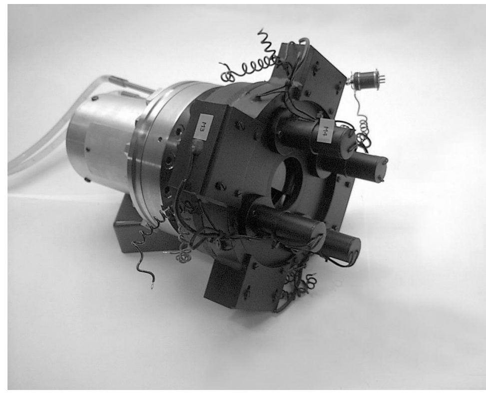

Fig. 1. A sketch of the ITANET camera showing the filter system and CCD dewar

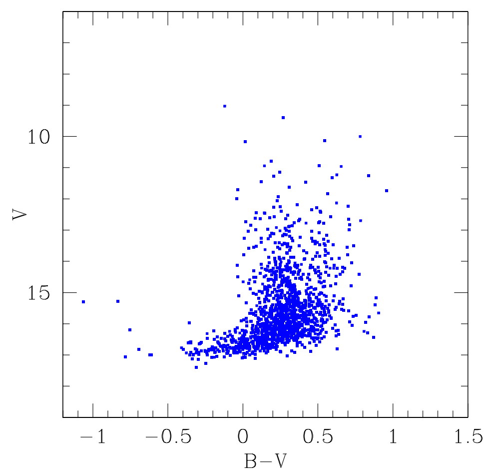

Fig. 2. The color magnitude diagram in the B and V Johnson filters for one of the RATS fields. Exposure times for the B and V images were 15 seconds.

2. Instrumentation

Wide field imaging will be performed using one of the CCDs manufactured by e2v for the cancelled Eddington mission. This CCD will be loaned by ESA to the project consortium in late winter 2006. In the meanwhile we have started the project using two other CCDs. The first CCD camera is called ITANET camera and the second one SITe camera. Table 1 summarize the main characteristics of the CCD cameras which will be used during the project.

2.1. The ITANET Camera

The ITANET project (ref) is an Italian national project whose aim is the study of Near Earth Objects. The CCD camera, that has been completely designed and realized at the Catania Astrophysical Observatory (see figure 1), will be used by the RATS project too. Due to its small field of view and to its low quantum efficiency, the CCD is a bare front illuminated device, the camera will not be used for the survey itself. Instead as it will be the only one equipped with a set of BVRI Johnson filter will be very useful for the characterization of the fields selected for the RATS search. An example of this kind of analysis is shown in figure 2.

2.2. The SITe Camera

The SITe camera is based on the SITe-424A back-illuminated 2048 × 2048 device. The CCD has been characterized at the Catania Astrophysical Observatory and its quantum efficiency is shown in Fig. 4. The CCD has been

Table 1. Characteristics of the CCD cameras

	ITANET	SITe	Eddington
Chip	KODAK KAF-4202	SITe-424A	e2v 42-C0
Format	2032 × 2044	2048 × 2048	2048 × 6144
Pixel Size	9.0 μm	24.0 μm	13.5 μm
Full Well	90000 e^-	200000 e^-	150000 e^-
Read-Out Speed	50 kpx/s	50 kpx/s	450 kpx/s
Read-Out Noise	8.4 e^- (50 kHz)	10 e^- (50 kHz)	5 e^- (450 kHz)
Read-Out Mode	Full Frame	Full Frame	Frame Transfer
Temperature	-40°C (Peltier)	-100°C (LN2)	-100°C (LN2)
Dark Current	2.5 e^-/pix/h	≤ 1 e^-/pix/h	2 e^-/pix/h
Dynamics	10000:1	20000:1	30000:1
Scale	0.9"/pix	2.3"/pix	1.3"/pix
Field of View	0.51°	1.31°	0.7 × 1.1°
Optical Filters	BVRI Johnson	None	None

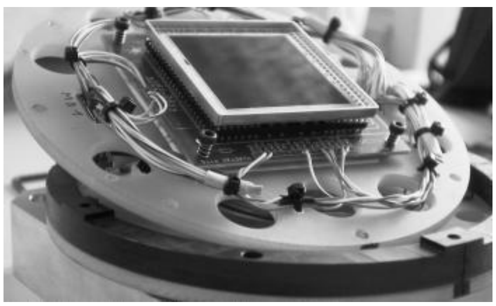

Fig. 3. The SITe CCD mounted on its cold finger before being placed inside the dewar

mounted inside a LN2 dewar. Cold finger, wire cabling and mechanics (see Fig. 3) have been realized at the Padua astronomical observatory. The window the sealed the dewar is a field flattener lens with a 1500 mm focal length. Presently the camera is mounted on the Cima Ekar Schmidt telescope where is undergoing focusing optimization procedures.

2.3. The Eddington Camera

The final CCD camera will use the CCD chips developed by e2v for the focal plane of Eddington (see figure 5). The CCD is a back illuminated frame transfer device. All the mechanical interfaces necessary to integrate the CCD inside the dewar presently hosting the

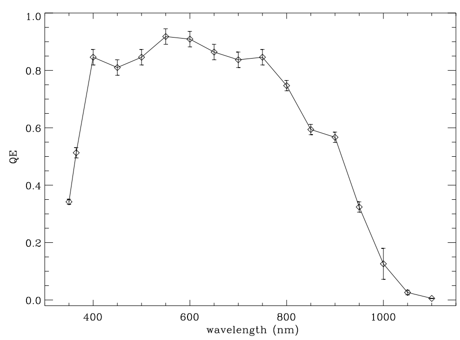

Fig. 4. The quantum efficiency curve of the SITe CCD obtained at the Catania Astrophysical Observatory

SITe CCD are being realized at Asiago and Catania.

2.4. The CCD controllers

To run the CCD cameras the RATS project will make use of the CCD controllers developed for the "Telescopio Nazionale Galileo" (TNG). At the moment we are using the old version of the controller based on the transputer whose main limitation is the read-out speed that cannot be greater than 50 kpix/s. The "new generation" of controllers (Bonanno et al. 2004), that we plan to use for the Eddington CCD, will over-

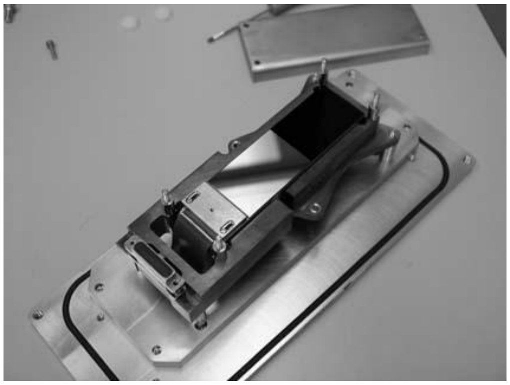

Fig. 5. The e2v 42-C0 Eddington CCD

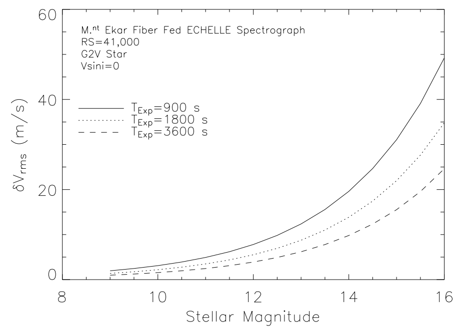

Fig. 6. Precision of radial velocity measurements as a function of stellar magnitude for different exposure times for the echelle spectrograph at Cima Ekar.

come this limitation allowing a rate up to 450 kpix/s.

3. Magnitude interval selection

We have already noticed that to detect a planetary transit we need high photometric accuracy and also that we need a spectroscopic follow up to confirm that the photometric variation is indeed due to a planet transit. This last requirement limits the range of magnitudes that we can sample during the survey. In fact, the limiting magnitude to reach a precision in the radial velocity measurements of 10 m/s using the echelle spectrograph at the Copernico Telescope in one hour exposure is (see figure 6) about 14. On the other side the minimum magnitude is set by the observational strategy. A 15 seconds exposure (as foreseen for the Eddington mission) at the Schmidt of Cima Ekar taken in integrated light easily saturates a star with visual magnitude of 13. The solution adopted to avoid CCD saturation is to defocus the telescope. However, one has to guarantee high S/N ratio for the weakest magnitude and also an adequate number of stars per square degree with brightest magnitude. We found that $m_V = 9$ is a good compromise between the number of target stars and the necessary defocus. The $FWHM$ of a stellar image can be considered as the convolution of seeing, diffraction and, in our case, defocusing:

$$FWHM^2 = seeing^2 + airy^2 + defocus^2 \quad (1)$$

Figure 7 shows an example of calculation of defocusing for a star with $m_V = 9$. To avoid troubles with CCD saturation we put a limit to the signal that can be collected at a given exposure time in a CCD pixel, in particular:

$$S_{pix} \leq 0.75 \times \mathrm{FullWell} - S_{sky} \times t_{exp} \quad (2)$$

where S_{sky} is sky background per pixel per second. Dividing the star total flux by S_{pix} one obtains the number of pixels over which to spread the signal. Multiplying this quantity for the pixel sky projection one obtains the area A which is related to the $FWHM$ of the stellar image (assumed to be a Gaussian) by the following expression $A = \pi FWHM^2$. Using then equation 1 one can calculate the amount of defocusing. Once the exposure time has been set the defocusing depends on the seeing, on the sky background and on the characteristics of the CCD.

4. Fields selection

The selection of the stellar fields that will be the target of the survey has been performed using the following criteria. First of all each of the fields has to be observable for at least 8 hours during the night which for the Cima Ekar observing site means $\delta \geq 13°$. Second to maximize the number of stars per square degree we will observe close to the galactic plane, that is $-40° \leq b \leq 40°$. Finally we divided the sky in

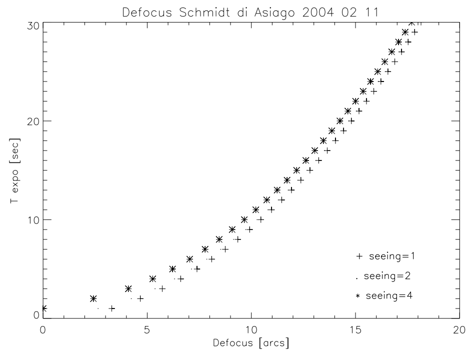

Fig. 7. Defocus calculation for a star with $m_V = 9$.

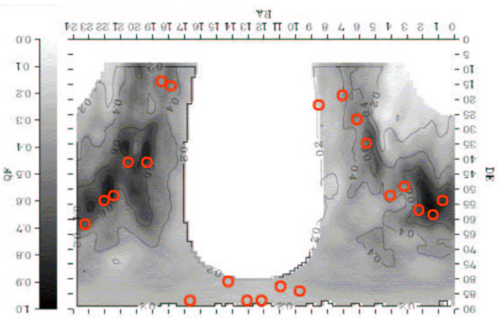

Fig. 8. RATS Field selection.

areas of 1 square degree and define for each of this area a factor of merit, QF:

$$QF = f(N/N_{max})(Nb_{max} - Nb)/Nb_{max} \quad (3)$$

where N is the number of stars in the selected area, N_{max} is the maximum number of stars in a field, Nb is number of stars with V magnitude lower than 9 and Nb_{max} is the maximum number of stars that can be tolerated in a field before staring to have problem with CCD saturation, f is a normalization factor. From this analysis, whose results are shown in figure 8, we selected three fields.

5. Observational Strategy

From stellar counts one finds that the number of stars per square degree with $9 \leq m_V \leq 14$ and spectral types F,G,K is about 200 Claudi et al. (2005b). With three fields selected and a CCD field of view of about 0.8° the total field of view covered by the survey would be 2.4°. This means that the total number of possible candidates is about 480 stars. The probability of having a hot Jupiter is about 1% while the probability of observing a hot Jupiter transit is 10% so in total the probability to observe a transit is 0.1%. This number has to be reduced by a factor that take into account the observing conditions (temporal coverage, duration of transit, period of transit etc). In particular the probability of observing a transit during a night is $P_t = \Delta T/T_{orb}$ where Δt is the total observing time and T_{orb} is the orbital period. The total probability of detecting a transit observing the same field for n nights is then

$$P = 1 - (1 - P_t)^n \quad (4)$$

Using typical numbers for observing conditions at Cima Ekar $\Delta t = 4.2h$, $n = 40d$, and $T_{orb} = 4d$ one obtains $P = 0.83$ which gives us a total probability of detecting a transit of 0.083%. This yields 0.4 transit per year and a total number of detected transits during the survey of 2. This number can be increased only increasing the sky coverage of the survey. The idea is to have for each of the fields selected a number of different but adjacent pointings. This solution has a drawback. In fact, for each true transit detection the number of expected false alarms varies between 6 and 60 Brown (2003). This has an impact on the spectroscopic follow up in terms of pressure on the echelle spectrograph. In figure 9 we have plotted the pressure on the Copernico telescope as a function of the number of observing nights for different numbers of pointings. Assuming that the maximum acceptable value of night sharing on the Copernico telescope is 40% of the total nights, the number of pointings compatible with this limit is about 7. An increase in the sky coverage by a factor of 7 will increase the number of detected transits per year to 2.8 and the total number to 14. Having several adjacent pointings will have an impact on the observational duty cycle too, because one cannot observe continuously the same field but one has to move among adjacent subfields. For 7 subfields assuming a 4 × 15 seconds exposure time for each pointing, 5 seconds to go from one pointing to the next and 30 seconds

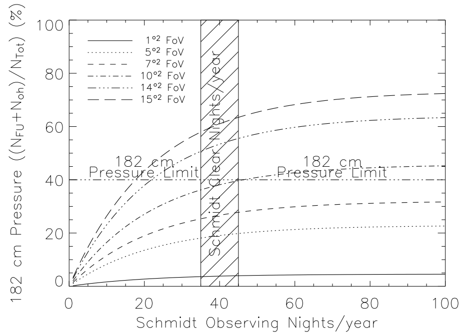

Fig. 9. Plot of the telescope pressure as a function of the number of observing nights for different numbers of pointings.

to go back to the first pointing yields a total duty cycle interval of about 10 minutes, that should give a fair sampling of the transit curve. We did not include the CCD readout time in the overheads because the Eddington CCD is frame transfer so the readout itself is done during the exposure.

6. The automatic data-reduction pipeline

The automatic data-reduction pipeline for RATS is based on the NOAO Image Reduction and Analysis Facility (IRAF), DAOPHOT Stetson (1987) and Fortran programs. It consists of a number of IRAF-CL scripts and Fortran programs which are invoked by a master shell script. The data-reduction process is initialized by a Linux shell script which starts first IRAF and then the master IRAF scripts. At startup of IRAF, the ”loginuser.cl” task is executed. It loads the required IRAF packages and defines the individual IRAF tasks of the pipeline and various IRAF environment variables. The shell master script creates the input- and output-file lists and starts the individual subtasks one after another.

The pipeline first reduces the images for bias and flat field in order to remove errors such as variations in pixel sensitivity, scratches on the lenses, noise etc. The pipeline then examines the images and matches each star with itself in different images. Finally a complex photometric analysis is performed where the brightness of every star is measured. When sufficient observations have been made (over several days) searches for changes in brightness can be made which might indicate the presence of a planet. The light-curves of all the candidate variable stars are plotted and then examined to determine if the changes in brightness are caused by a planet or another astronomical phenomenon (i.e. eclipsing binaries).

The data reduction is recorded in a logfile so that if certain critical limits are exceeded, warning and/or error messages are registered in it. This allows an easy overview of the reduction process of a whole night. Upon checking these files, the astronomer has the possibility to edit parameters in the parameter file and, subsequently, to rerun individual data-reduction tasks interactively.

7. Conclusions

RATS is a five year long program whose goal is twofold: 1) to discover at least ten new extrasolar planets using the transit method; 2) to test the observational, data reduction and archiving strategy of a future space mission devoted to this aim. The new discoveries are expected to give some insight in the mechanism of planetary formations, in the properties of the environmental conditions, the hot Jupiter problem. Parallel science in the fields of stellar variability (pulsating stars, magnetic activity, eclipse variables etc) and spatial variability (minor bodies of the solar system) will be pursued. An automatic pipeline has been written allowing for a full reduction of RATS images..

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