PROSPECTS FOR BROWN DWARF AND EXTRASOLAR PLANET RESEARCH WITH THE GTC AND THE LMT

E.L. Martín[1], C. Allen[2], D. Barrado y Navascués[3], H. Deeg[1], E. Solano[3], A. Poveda[2], V.J.S. Béjar[4], M.R. Zapatero Osorio[3]

RESUMEN

ABSTRACT

The topic of brown dwarf and extrasolar planet research with the GTC and the LMT was discussed during a half day workshop at Universidad Nacional Autonoma de Mexico. This paper summarizes the contributions presented at that Workshop plus additional contributions from members of the Spanish Network for extrasolar planets. Specific observational projects, which can be carried out with the planned instruments for the GTC, including first light ones, are explained in some detail. These projects are the following: our coolest neighbors, brown dwarfs in wide binaries, brown dwarfs and planetary mass objects in Orion, follow-up of transiting extrasolar planets and verification of planet candidates, the search for ultracool companions to nearby stars, brown dwarf binaries and disks around brown dwarfs.

Key Words: **STARS: PRE-MAIN SEQUENCE — STARS: VERY LOW-MASS STARS, BROWN DWARFS — EXTRASOLAR PLANETS**

1. INTRODUCTION

A half day workshop on brown dwarfs and exoplanets was held at the Universidad Nacional Autonoma de Mexico (UNAM) on 19 February 2004, following the II International Workshop on Science with the GTC and the LMT. The attendees were: Christine Allen (UNAM), David Barrado y Navascués (LAEFF), Jorge Alejandro Hernández Alcántara (UNAM), Eduardo Martín (IAC), Victor Sánchez Béjar (GTC), Arcadio Poveda (UNAM), Enrique Solano (LAEFF) and Maria Rosa Zapatero Osorio (LAEFF).

A list of possible topics for developing a strategy for observations of brown dwarfs and exoplanets with the GTC was discussed. Further contributions were solicited during a meeting of Spanish exoplanet investigators shortly after. This paper is a compendium of the contributions that have been received from several researchers. It demostrates the wide variety of studies of substellar-mass objects that can be carried out with planned instruments for the GTC and the LMT, and it shows a high level of interest of this scientific community in the GTC.

2. THE SOLAR NEIGHBORHOOD

The most numerous population in the solar neighborhood is that of the M dwarfs as shown in Figure 1 (adapted from Henry 1998). Large surveys such as DENIS, SDSS and 2MASS have identified a new population of ultracool dwarfs (spectral types L and T). The L dwarfs are characterized by weak or absent TiO bands and very broad resonance lines of NaI and KI in the optical spectrum (Martín et al. 1997, 1999; Kirkpatrick et al. 1999), and the T dwarfs are characterized by methane bands in the near-infrared spectrum (Burgasser et al. 1999; 2002). L dwarfs span the effective temperature range between ~2200 K and 1500 K (Basri et al. 2000), while T dwarfs have effective temperatures between 1500 K and 800 K (Knapp et al. 2004).

Deeper surveys such as CFHTLS (Mellier 2004) and UKIDSS (Hambly et al. 2003) are expected to reveal even cooler dwarfs (Teff<800 K). The GTC first light instruments ELMER (García Vargas et al. 2003) and OSIRIS (Cepa et al. 2003) will allow the spectroscopic follow-up of ultracool dwarf candidates at optical wavelengths, and EMIR (Garzón et al. 2003) will allow to obtain near-infrared spectroscopy. These observations will be crucial to establish the nature of the ultracool dwarf candidates (Martín et al. 1999; Kendall et al. 2004). The optical spectroscopy is the most accurate way of characterizing late M and L dwarfs, while the near-infrared spectroscopy is the best and only way of characterizing T dwarfs.

For the coolest dwarfs it may happen that a new spectral class (letter H and/or Y) may have to be defined. A more complete census of ultracool dwarfs

[1]IAC, La Laguna, Spain.
[2]Instituto de Astronomía, UNAM, Mexico.
[3]LAEFF-INTA, Madrid, Spain.
[4]IAC, GTC project, Spain.

is necessary to estimate the overall substellar mass function in the galactic disk. Estimates based on the known ultracool dwarfs in open clusters and the field indicate that brown dwarfs may be as numerous as stars (Béjar et al. 2001; Chabrier 2003). Thus, it is likely that there are many discoveries ahead of us for the future use of the GTC instruments.

3. BROWN DWARFS IN WIDE BINARIES

For the purpose of exploring observational projects with the GTC, we divide wide binaries (those with semimajor axis >60 AU) in two groups: (a) Wide binaries in the thick disk and halo, (b) Wide binaries in the disk (general field and young clusters).

3.1. *Wide binaries in the thick disk and halo*

Allen et al. (2000) published a list of common proper motion wide binaries among the low metallicity high velocity stars studied by Schuster & Nissen (1989) with Stromgren photometry. The secondaries of these primaries have not yet been characterized spectroscopically, and their photometry is incomplete. These data would be important for a better determination of the faint part of the luminosity function for metal-poor stars because the distances to the primaries are known.

It could also be possible to establish empirically the Kumar limit for objects with low metallicity with a search for faint companions (brown dwarfs) among these systems. This search is promising because the brightness contrast between the secondaries and possible tertiaries would be small. Moreover, it is known that the frequency of triple stars and higher order multiples is significant. If a brown dwarf tertiary is detected, we would know inmediately its bolometric luminosity because they would be companions of stars with known distance and metallicity (and sometimes even known age). A recent study by Chanamé & Gould (2003) has found a group of wide binaries in the halo and disk, and has given approximate distances and JHK photometry. Even though the available information for these binaries is not as complete as for those of Allen et al., it would also be interesting to search for brown dwarfs among their secondaries.

3.2. *Wide binaries in young clusters*

Poveda & Hernández-Alcántara (2003) have found about 60 common proper motion wide binaries in the Orion Nebula Cluster (ONC). The age of this cluster is only about 1 Myr. The faintest secondaries of these binaries are particularly interesting because some of them could be brown dwarfs. From the study of Hillenbrand (1997) it has been inferred that 25 secondaries have masses reaching below the substellar borderline. 13 of them have ages of less than 0.1 Myr, so they are extremely young. These 25 brown dwarf candidates need a better photometric and spectroscopic characterization that will yield more accurate estimates for their masses. Their magnitudes are so faint that a search for even fainter tertiaries is promising. To confirm the multiplicity of these objects, it would be important to carry out an astrometric program with adaptive optics, taking advantage of the time elapsed since the previous astrometric work of Jones & Walker (1988).

4. THE ONE THOUSAND ONE WORLDS OF ORION: THE EFFECT OF ENVIRONMENT.

So far, several young clusters (the Pleiades, Alpha Persei, IC2391, Sigma Orionis) and star forming regions (Taurus-Auriga, Chamaeleon, IC348, rho Oph, Trapezium), have been surveyed with the double purpose of finding brown dwarfs (specifically, searching for a minimum mass) and describing the Mass Function (MF) in each association. On one hand, a cluster substellar MF minimum mass would impose a very strong constraint to the proposed formation mechanisms and the physics behind the dominant one (more than one might be acting). On the other hand, a detailed study of different Mass Functions would entail the knowledge of the MF evolution (due to effects such as the mass segregation within each association and the disaggregation due to the galactic gravitational well), the shape at the beginning of an association (the Initial Mass Function, IMF), and the impact upon it of the initial conditions (mass and density of the initial molecular cloud, proximity to other complexes, metalicity, magnetic fields).

However, the studies carried out up to date have been, at best, partial. They either cover only a small part of a particular association (such as in the case of the open clusters), or use different observational tools (such as different filters, making comparison and interpretation more difficult) or are hampered by other effects such as dynamical ranges of each study, which survey a medium to small mass range and lack completeness across the range of the stellar and substellar populations. In any case, the first step toward a comprehensive view have been undertaken. For instance, a massive effort is underway with the CFHT and the MegaCam, which is studying large fractions of the volume covered by several open clusters and star-forming regions (Bouvier et al. 2004, in prep). Moreover, some results in the

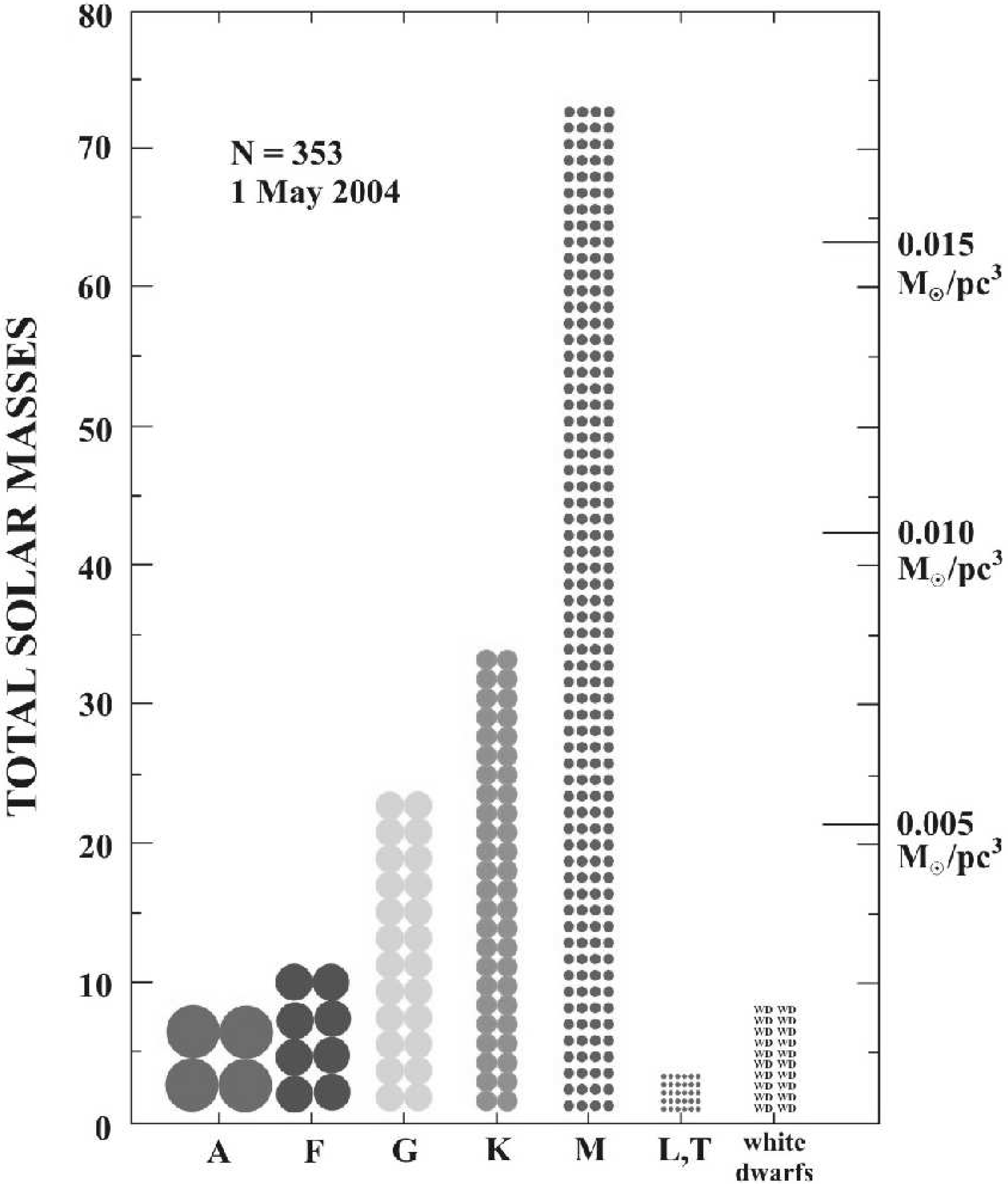

Fig. 1. The present census of the solar neighborhood within 10 parsec.

Taurus-Auriga complex indicate that its IMF might have a smaller population of brown dwarfs, when compared with other young, more compact, stellar nurseries (Briceño et al. 2002; Luhman et al. 2003).

In order to avoid all these problems, it would be desirable to center efforts on samples nearby enough to be reachable with 4-10 meter class telescopes, young enough so dynamical evolution has not started (in addition, its members would be brighter than those belonging to older associations) and diverse enough so we would face different controlled conditions. Such a region does exist: its name is Orion, composed by a myriad of different environments with distinct types of star-formation and dark molecular clouds.

The Orion complex, located at about 400 pc, is both a jewel of ancient mythology and modern Astronomy. The profile of the Hellenic hero is delineated by several star cradles such as the Trapezium (θ Orionis) in the sword, dark and reflexion molecular clouds such as the Horse Nebulae in one of the hips, OB-T associations such as the Lambda Orionis SFR in the Head, or young clusters such as Sigma Orionis, just below the Belt. In fact, young and massive stars percolate the whole area. In some cases they are very conspicuous, such as in the case of the Belt itself (ϵ, δ, and ζ Orionis) or o Orionis (south-west of Trapezium), and might preside over star clusters by their own right.

A typical case is provided by the hero's head, the Lambda Orionis star-forming region (SFR). The O8 III λ^1 Orionis star is located in the center of a ring of dust and gas nine degrees in diameter, which was detected by Zhang et al. (1989) using the IRAS satellite. This structure is complementary of a neutral hydrogen shell discovered half a century ago (Wade 1957, 1958). Additionally, the dark molecular clouds Barnard 30 and 35 (B30 and B35) lie within the area. Recently, Dolan & Mathieu (1999, 2001, 2002) have discovered a distinct population of T Tauri stars around the λ^1 Orionis star, B30 and B35; and Barrado y Navascués et al. (2004, see also this volume) have found a large number of very low mass stars and brown dwarfs around the Lambda Orionis cluster, also called Collinder 69. The complex also contains other structures, such as clustering of B stars and IRAS sources, as Figure 2 illustrates.

Similar studies have been conducted in the Trapezium, Sigma Orionis and other areas in Orion. Therefore, the Orion complex, due to its richness, is a unique hunting ground. A study designed to survey specific areas within the complex might yield a crop of very important results for understanding star formation. The advent of the GTC provides the opportunity to start this intensive program. The preparatory campaigns have to be initiated as soon as possible. The necessary steps include:

- Target selection based on database analysis. This step implies an extensive survey of the published literature and data coming from space missions. As an example, ROSAT data provide information regarding the clustering of X-ray sources, which might betray the presence of an unknown young association. The Sigma Orionis Cluster was discovered using this method (Wolk et al. 1996; Walter et al. 2000).

- Optical survey. Once the target areas have been selected, it is necessary to carry out an optical campaign which allows an initial identification of candidate members in each association. The Wide Field Camera at the 2.5-m Isaac Newton Telescope in La Palma, with its large field of view ($\sim$30$\times$30 arcmin) is an adequate tool for this purpose. The filters R, I and Z optimize this type of search. Since long exposure times are required (the aim is to reach about I=25 mag), together with a large spatial coverage (about a dozen square degrees per SFR or cluster), a large amount of time is required (several weeks per season, during several years).

- Near infrared follow-up. Down to $Ks\sim15$, the 2MASS All Sky Survey (Cutri et al. 2003) provides J, H and Ks photometry. For fainter objects, INGRID at the WHT or NICS at the TNG can be used on a candidate by candidate basis. The Calar Alto observatory has a unique instrument for this purpose, Omega2000 at the 3.5-m telescope, capable of covering 15$\times$15 arcmin. Therefore, it is very efficient when used in a survey mode.

- Low-resolution optical spectroscopy. WYFFOS, a multifiber spectrograph located at the WHT, fulfills this task. This steps allows the rejection of interlopers (old stars in the line-of-sight, giant stars behind the target or red galaxies beyond) in a very efficient way.

- Medium- and high-resolution optical spectroscopy. A battery of tests requires the use of GTC and UES (or any successor). This is the case for the detection of lithium at 6708 Å, the analysis of gravity sensitive features such as NaI8200 and KI7700 Å, rotational and radial velocity studies. In some cases, ELMER, available

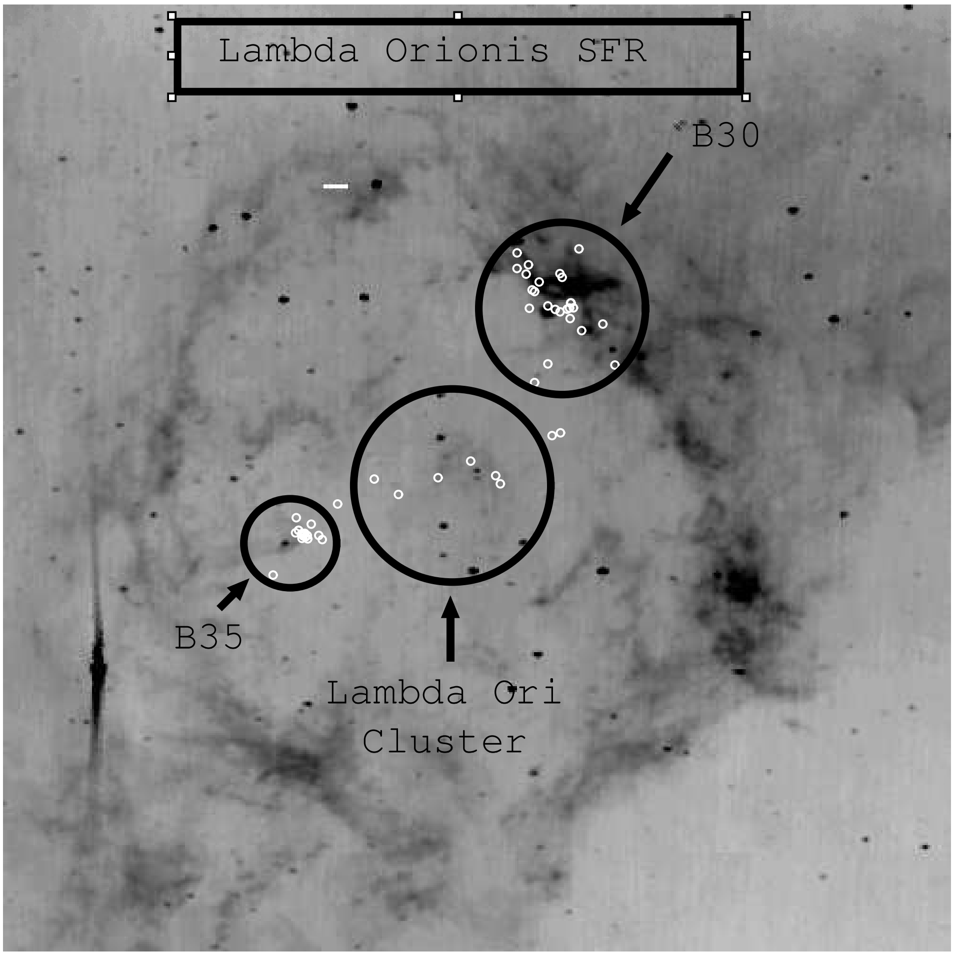

Fig. 2. IRAS image at 12 microns of the Lambda Orionis star forming region. The size of this image is 12 by 12 square degrees.Small circles correspond to Classical T Tauri stars.

at first light, can play a very important role in nailing down the nature of the candidates.

- Low- and medium-resolution near infrared spectroscopy. Some of the most interesting objects will be very faint and red. They are the isolated planetary mass objects, with masses below the deuterium burning at 13 Jupiter mass. EMIR at GTC will suffice for this purpose.

- High-resolution near infrared spectroscopy. A sensational result would be the identification of a planet orbiting a very low mass star or brown dwarf whose age is well known. This is most efficiently done in the infrared domain. This niche is presently not covered at the GTC. An instrumental proposal such as NAHUAL (Martín et al. 2004, in prep.) will be specifically tailored for this goal.

- A search of low mass companions should be carried out, by using AO (INGRID and TNG) or the HST. Additionally, CanaryCam can produce important results in the mid-infrared where the contrast between the central objects and planets is optimal.

As can be seen, this comprehensive array of observations, in a time span of a few years, can provide new clues of the stellar and substellar formation, the formation of planetary systems within them, and the effect of the environment.

5. EXTRASOLAR PLANETS

5.1. *Transiting Planets*

Planets discovered with the transit method offer several ways to gain further information about their nature. This applies to planets that may be discovered with space missions like COROT or Kepler, but the most suitable planets for further investigations with the current generation of new large telescopes are hot giants around bright stars. These give both the largest transit amplitudes and the best signal-to-noise ratio in any experiment with photon-count limited sensitivity. The potential of further studies on such a system has been demonstrated in the case of the transiting planet HD209458b; it is the best studied exoplanet for which all major orbital parameters are known, and the only one where an atmospheric component has been detected, by the comparison of spectra taken 'on' and 'off' transit (Charbonneau et al. 2002; Vidal-Madjar et al. 2004). Extensive modeling of giant planet atmospheres and expected transmission spectra has been undertaken (e.g. Seager and Sasselov 2000, Brown 2001), which shows that besides abundances and temperature, spectral features will depend also on the presence and altitude of cloud layers. They will therefore be able to distinguish atmospheric models. Brown (2001) indicates as a general requirement for transmission spectral diagnostics a S/N of at least 1000 and resolving powers ranging from 10^3 to 10^6. With the proposed NAHUAL instrument on the GTC, the detection of further features of HD209458b's atmosphere, such as a CO feature at 2.3 micron may be achieved.

The detection of further transiting planets orbiting bright stars, allowing similar studies, is an important goal. The project of a permanent all-sky survey of transits (PASS, Deeg et al. 2004) is specifically dedicated to this goal. Several other projects are dedicated to more distant stars or smaller planets. For example, the first transiting exoplanets from the OGLE-III survey appear to have been confirmed with Keck/HIRES observations (Konacki et al. 2003).

Besides spectroscopy, additional insights from transits may be gained from photometry that combines high S/N and short intergration times, and possibly, several filters. The need to employ a very large telescope depends on the particular case, but typically, the achievable S/N needs to be maximized. For example, the precise timing of the center of a transit requires both high S/N and short integration times, and deviations from periodicity could reveal the presence of further bodies in the system (Sartoretti & Schneider 1999). Precise measurements of the duration of a transit, from first to last contact, may reveal slow variations from changes in the inclination of the transiting system from precession or proper motion. Transit durations observed in narrow-band filters of absorbing lines might also show variations of the apparent planet diameter when compared against continuum wavelengths. This would be indicative of the atmospheric scaleheight of its constituents. In the HD209458 system, a variation of the effective planet radius of 100 km would cause about 1.5 sec variation in transit duration, but atmosphere models indicate radius variations up to 5000 km in some lines. If present, these would cause transit duration variations of over one minute, which may be well observable using the fast photometry mode of ELMER or OSIRIS.

There are several phenomena which may cause transit-like lightcurves, and which may not be distinguishable with the data from the detection device, thereby requiring follow-up observations. These may be (Brown 2003) grazing eclipsing binaries, eclipses between low-mass stars and giant stars, and 'normal' eclipsing binaries with large amplitudes whose light is diluted by a brighter star (which may be associated with the binary or just appear nearby). A step-like procedure has been proposed by Alonso et al. (2003) to reject false alarms, starting with rejection tests that are simple and light on resources, in terms of telescope size and time required, and advancing to more demanding ones. Transit light curves in multiple colors and with sufficient S/N may show color-signatures that are incompatible with a planet. Imaging with adaptive optics may show that a transiting system is really a double or triple star. This by itself would not reject a transit's planetary nature, but obtaining time-series with high spatial resolution may show that one of several close components is indeed an eclipsing binary. Radial velocity measurements might show velocities appropriate for eclipsing binaries (not very high resolution is needed, but high S/N in the case of background binaries that produce asymmetries in the line profiles) or in the contrary, the small radial velocities proper of a planet may be detected. While detection of radial velocities from planets requires very stable high resolution spectrographs, it should be noted that this is the only test that is able to confirm positively the planetary nature of a transiting system, whereas the other tests mentioned are able to detect false alarms, but do not verify a planet. For all these tests, the need to employ a very large telescope depends on the parameters of the system that is under study and has to be decided on a case-by-case basis. However, similar to transit detection experiments, whose detection-power increases with S/N, the diagnostic power of these tests increases with S/N, and consequently a variety of needs for a large telescope like GTC can be expected, especially in order to clarify faint transit candidates detected by space missions.

5.2. *A new class of planets*

COROT (COnvection, ROtation and planetary Transits) will be the first mission able to detect Earth to Uranus–class planets using the transit method. This goal will be achieved by monitoring up to 12000 dwarfs stars with visual magnitudes from V=11 to V=16 continuously during five months. Five of these fields will be observed during the expected mission lifetime (2.5 years). More detailed information about the *COROT* mission can be found at: http://www.astrsp-mrs.fr/projets/*COROT*/.

COROT will open a new window in the study of the extrasolar planets. The detection of a new class of planets (the "Earth to Uranus–class") will require a characterization work similar to what is being done for the Jupiter-class planets detected with the radial velocity method. In particular, these new planets will be smaller in size and mass and it will be very interesting to check if the high metallicity trend found in the Jupiter-like planets is also present in this new class. This will have inherent implications in the planetary formation theories (e.g., in the "primordial high-metallicity" scenario one could expect that the formation of smaller planets would not require as large amount of primordial rocky material as for the giants planets, the overabundances being, therefore, more modest). On the other hand, the planets detected so far are in the solar vicinity (at distances less than 100 pc) and *COROT* will be able to look much further. This will allow to check the evidences which indicate that, at any Galactocentric distance, the stars with planets possess metallicities above the mean of nearby field stars (Laws et al. 2003).

The determination of the chemical abundances of the stars with planets requires spectroscopic observations of high resolution (R=40,000-60,000) and high signal-to-noise ratio (S/N=200-300) covering a large wavelength range. Given the visual magnitudes of the *COROT* targets, a 10-m class telescope is needed to perform such an analysis. Although GTC does not contemplate a high resolution spectrograph among the Day-1 instrumentation, the possibility of bringing the Utrech Echelle Spectrograph (UES) to GTC soon after the beginning of the scientific operations is presently under study. Preliminary tests indicate the feasibility of obtaining the necessary signal–to–noise for the range of magnitudes observed by *COROT* with reasonable observing times using GTC/UES. A high resolution near-infrared spectrograph (NAHUAL) is also under consideration. Chemical abundances could be derived using near-infrared photospheric lines such as KI, NaI, FeI, CO and OH bands. The near-infrared lines are particularly useful for some elements, such as O, and for M- and cooler spectral types.

5.3. *Chemical abundances of host stars*

Soon after the first detection of a star with planet (Mayor & Queloz 1995), it was seen that this new type of objects showed systematically higher values of [Fe/H] than the nearby stars with similar physical parameters and without planets. This result is of great relevance as metallicity is the only link known so far between the presence of planets and a stellar photospheric feature.

To date, two possible explanations have been proposed to explain these anomalously high values of metallicity: the "self-enrichment" and the "primordial high-metallicity" scenarios. In the former, the high metallicities are due to the pollution of the convective envelope caused by the inward migration of a planet toward the central star or by the transfer of material from the protoplanetary disk. Although some indirect clues may support this hypothesis—cf. detection of Li^6 in the star with planet HD82943 (Israelian et al. 2001), differences in iron between 16 CygA and 16 CygB (Laws & Gonzalez 2001)—most of the observational evidences are in favor of the "primordial high-metallicity" hypothesis in which high metallicity values in the parent cloud would imply a higher presence of rocky material in the nebula leading to enhanced planet formation (Santos, Israelian & Mayor 2004). This result appears to support the classical planetary formation scenario for giant planets close to stars based on the core accretion and subsequent migration compared to the disk instability scenario proposed by Boss (2002) where the planet formation is almost independent of metallicity.

6. VERY LOW-MASS COMPANIONS TO NEARBY STARS

The discovery of very low-mass companions within a few arcseconds of nearby stars has been made possible by Adaptive Optics (AO) systems (Martín et al. 2000; Potter et al. 2002) down to brown dwarf masses (13-75 Jupiter masses). However, extrasolar planets are even fainter. The large magnitude contrast between planets and the host stars cannot be reached with current AO facilities, except when the planets are extremely young. The contrast is mainly limited by the instability of the point spread function (PSF) delivered by the AO system. This makes it impossible to subtract away the light scattered outside the first Airy ring. One possible way to increase the contrast is quasi-simultaneous observation in and out of two adjacent spectral bands, where the very low-mass companions have very different fluxes. This method works particularly well for the coolest known dwarfs (T-type) which have methane absorption bands in the near-infrared spectra. For example, differential simultaneous imaging has been carried out with the TRIDENT camera on the Canada-France-Hawaii 3.6-meter telescope, reaching a contrast of 10 magnitudes in the H-band at 0.5 arcseconds (Marois et al. 2003). A concept for carrying out differential imaging with the GTC/AO instrument FRIDA, is currently under consideration. For massive planets (about 5 Jupiter masses) and moderately old ages (up to about 1 Gyr), Canarycam may be the instrument of choice for detection at 10 microns in nearby stars because of the predicted hump for extremely cool substellar objects (Burrows, Sudarsky & Lunine 2003).

Astrometry of double brown dwarfs with AO is yielding the first dynamical masses for these objects (Lane et al. 2001; Bouy et al. 2004). High-resolution spectra of each component in the very low-mass binary system Gl 569 B has been obtained with Keck AO NIRSPEC by Zapatero Osorio et al. (2004), allowing the direct determination of individual masses for the components. The main limitation of this kind of work is that there are very few stars in the sky that are bright enough for natural guide wavefront sensing and that also have a very low-mass binary companion within the isoplanatic angle. The advent of commercially available laser AO systems will increase by more than tenfold the number of very low-mass binaries for which the masses can be derived with GTC/AO. The masses of many brown dwarfs in binaries could be measured with the GTC/AO with NAHUAL combination.

7. THE IMPACT OF THE LMT: DISKS AROUND BROWN DWARFS

With its 50-m antenna, the Large Millimeter Telescope (LMT) located in Mexico will have superb sensitivity in the wavelength range between 1 and 3 mm. It is expected to surpass ALMA for pointed observations. The first detections of brown dwarfs at millimeter wavelengths have recently been reported by Klein et al. (2003). A brown dwarf in the young open cluster IC348 and a brown dwarf in the Taurus star-forming regions were detected at 0.85 mm with the JCMT on Mauna Kea, and at 1.3 mm with the 30-m IRAM telescope in Pico Veleta. These brown dwarfs are thought to be extremely young (age$\sim$1 Myr). The dust masses inferred from these observations are in the range of 1 to 20 earth masses. The mass ratio between the primaries and the disks appear to be similar to T Tauri stars. Accretion activity similar to T Tauri stars has also been observed in the emission lines of some very young brown dwarfs (Barrado y Navascués & Martín 2003; Barrado y Navascués et al. 2004).

With the LMT a large program to study the frequency and properties of dust disks around young brown dwarfs will become feasible. This situation is similar to what happened with T Tauri stars over a decade ago when IRAM allowed a systematic study of dust emission (Beckwith et al. 1990). LMT will have a long lasting impact by allowing the detection of disks around hundreds of brown dwarfs in the nearest star-forming regions (rho Oph, Serpens, Taurus) and very young open clusters (IC 348, Orion). The GTC can provide fresh brown dwarfs for study with the LMT via low-resolution optical spectroscopy with ELMER and OSIRIS. The GTC data will allow to estimate the age of brown dwarf candidates through the use of spectral features sensitive to surface gravity (Martín et al. 1996, 2001; Béjar et al. 1999). The candidates could come from large imaging surveys such as those currently ongoing with CFHT/Megacam.

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Christine Allen: Instituto de Astronomía, UNAM, Apartado Postal 70-264, México, D.F. 04510, (chris@astroscu.unam.mx).
David Barrado y Navascués: Laboratorio de Astrofísica Espacial y Física Fundamental, INTA, Apartado Postal 50727, E-28080 Madrid. SPAIN (barrado@laeff.esa.es).
Hans Deeg: Instituto de Astrofísica de Canarias, C/ Via Láctea, s/n, E-38200 La Laguna (Tenerife). SPAIN (hdeeg@iac.es).
Eduardo L. Martín: Instituto de Astrofísica de Canarias, C/ Via Láctea, s/n, E-38200 La Laguna (Tenerife). SPAIN (ege@iac.es).
Arcadio Poveda: Instituto de Astronomía, UNAM, Apartado Postal 70-264, México, D.F. 04510, (poveda@astroscu.unam.mx).
Victor Sánchez Béjar: Instituto de Astrofísica de Canarias, Gran Telescopio de Canarias project, C/ Via Láctea, s/n, E-38200 La Laguna (Tenerife). SPAIN (vbejar@iac.es).
Enrique Solano: Laboratorio de Astrofísica Espacial y Física Fundamental, INTA, Apartado Postal 50727, E-28080 Madrid. SPAIN (Enrique.Solano@laeff.esa.es).
Maria Rosa Zapatero Osorio: Laboratorio de Astrofísica Espacial y Física Fundamental, INTA, Apartado Postal 50727, E-28080 Madrid. SPAIN (mosorio@laeff.esa.es).