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Status of the physics of substellar objects project

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Abstract. A full understanding of the properties of substellar objects is one of the major challenges facing astrophysics. Since their discovery in 1995, hundreds of brown dwarfs and extrasolar planets have been discovered. While these discoveries have enabled important comparisons with theory, observational progress has been much more rapid than the theoretical understanding of cool atmospheres. The reliable determination of mass, abundances, gravities and temperatures is not yet possible. The key problem is that substellar objects emit their observable radiation in the infrared region of the spectrum where our knowledge of atomic, molecular and line broadening data is poor. Here we report on the status of our PoSSO (Physics of SubStellar Objects) project. In order to understand brown dwarfs and extrasolar planets increasing more like those in our solar system, we are studying a wide range of processes. Here we give an update on the project and sketch an outline of atoms, molecules and processes requiring study.

Key words: stars: structure – planets: extrasolar

1. Introduction

At a Cool Stars meeting in Florence, Italy in 1995 the field of substellar astrophysics was born. The discovery of definitive signals from the brown dwarfs Gliese 229B (Nakajima et al. 1995) and Teide 1 (Rebolo, Zapatero Osorio & Martín 1995) and the extrasolar planet 51 Peg b (Mayor & Queloz 1995) were announced. The low luminosity and strong methane bands shown for Gliese 229B indicated a temperature of less than 1500 K and luminosity of 10^{-5} that of the Sun. No star can be so cool and faint. The acceptance of brown dwarfs by the community was immediate. While the discovery of the first brown dwarf was extremely exciting coming more than 30 years after the prediction of then so-called 'dark stars' by Kumar (1962) and Hayashi (1961), it was somewhat eclipsed by the announcement of the 'first' extrasolar planet. In fact the announcement of the discovery of an extrasolar planet had been made many times (e.g., discussed by Bell, http://www.public.asu.edu/∼sciref/exoplnt.htm) in the 400 years since Giordano Bruno was executed in 1584 for promoting the idea that there might be other worlds around other stars. The 1995 announcement by Mayor & Queloz (1995) was different; it was almost immediately confirmed and added to by Butler & Marcy (1996). The full acceptance

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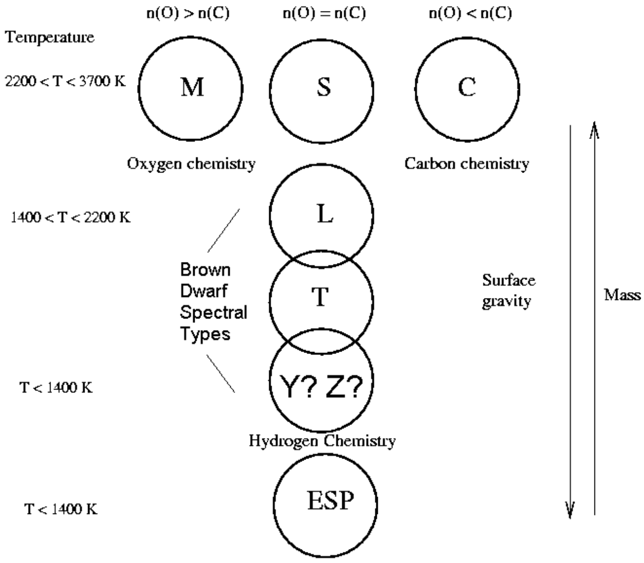

Fig. 1. The molecular composition of stellar atmospheres divides into two classes: oxygen-rich and the less common carbon-rich. There is also a third rare class of S stars where carbon and oxygen abundances are close to unity. In the objects of low-mass objects most of the Hydrogen is locked in H_2 and most of the Carbon in CO for LMS and BD, and CH_4 for BD and ESP, with excess Oxygen for oxygen-rich objects bound in molecules such as TiO, VO and H_2O, and with excess Carbon for carbon-rich objects, bound in molecules such as HCN, CH_4 and HCCH.

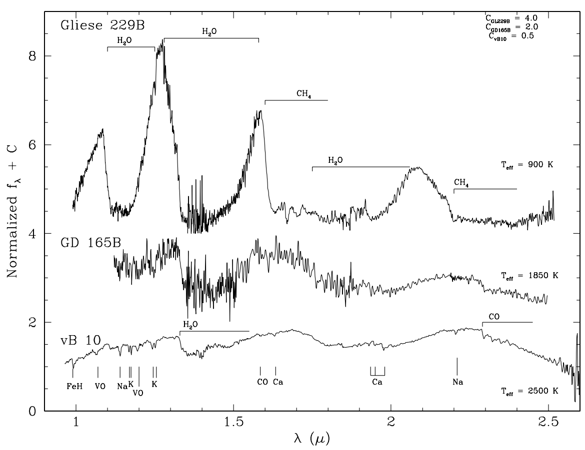

Fig. 2. The transition from M to T dwarf spectra across the infrared region showing the primary molecular and atomic absorption features (from Jones et al. (1994) and Oppenheimer (1999)). The figure shows vB 10 (M8), GD 165B (L4) and GJ 229B (T4).

of extrasolar planets has taken a little longer with confirmation of 51 Peg b by many groups and the signature of extrasolar planets using several different techniques on the same target, e.g., HD209458 by radial velocity and transit (Henry et al. 2000; Charbonneau et al. 2000).

In addition to bona fide brown dwarfs and extrasolar planets the discovery has probably also been made of another class of objects straddling brown dwarfs and planets – so called planetary mass objects or sub-brown dwarfs (e.g., Tamura et al. 1998). We can now study more than 100 extrasolar planets, 300 brown dwarfs and some 100 sub brown dwarfs. Unfortunately the interpretation of their infrared spectra, generally the only spectral region where they are bright enough to observe, is badly hampered by a lack of high quality input data in the infrared for the modelling of their atmospheres. Apart from these relatively newly discovered objects the lack of infrared data is also an issue for the study of M giants (the dominant population by luminosity of elliptical galaxies), S stars (where the carbon and oxygen abundances are similar) and C stars (where the carbon abundance dominates over Oxygen). Apart from wanting to understand the properties of our cool neighbours (e.g. Fig. 1), there are general questions relating to cool stars from cosmology (are some of the low mass stars primordial?), from star formation (does the initial mass function vary among star formation regions, and is there a lower mass limit below which no objects form?) and Galactic dynamics (how much mass is stored in substellar objects?).

2. Stars to planets

There are significant unresolved issues in the field of low-mass stars (LMS), brown dwarfs (BD) and extrasolar planets (ESP) that hinder our understanding of these objects. Examples include:
(1) The effective temperature scale and its correlation with spectral type are not yet properly determined: some objects which fall within the same spectral type show substantial differences in their energy distribution and this suggests different effective temperatures;
(2) metallicity and surface gravity (and hence ages) remain controversial: colour-colour diagrams, usually used as indicators, do not yet reproduce the broad-band fluxes within a reasonable error. An alternative and potentially powerful way of determining both metallicity and surface gravity is spectroscopically by comparing observed with synthetic spectra. At present the poor quality of the data available for this leads to fits where the temperature and metallicity are too correlated to be reliably determined independently (e.g. Viti et al. 2002).
(3) brown dwarfs do not burn Hydrogen but, depending on mass, may burn D or Li. The burning limits for D and Li, so-called ‘lithium test’ and ‘deuterium test’, could, given the necessary spectroscopic data, be used to determine the true substellar nature of ultracool dwarfs;
(4) brown dwarf formation: how can a brown dwarf form when its mass is at least 10 times smaller than the typical Jeans mass in star forming molecular clouds? Once it has formed, how can it avoid substantial further accretion of gas? What prevents them exceeding the hydrogen burning mass limit?
(5) The distinction between ESPs and BDs; some BDs are less massive than the most massive planetary companions (known as sub brown dwarfs or planetary mass objects); hence the use of a simple mass-based definition to distinguish between stars and planets is dubious.
(6) The trajectory of metal-free stars on the HR diagram: recent observations of highly metal deficient dwarf stars raise

Table 1. Atoms, molecules, dust compounds and mechanisms relevant for cool objects . We have made our selection of atomic lines based on Lyubchik et al. (2004). The bold species show immediate priorities for PoSSO. The species in italic denote those for which we have measurements in hand from our PPARC and Royal Society programmes (e.g., Blackwell-Whitehead et al. 2005a,b).

Metal-free	Oxygen-rich	Carbon-rich
HeH^+, H_3^+, **LiH**, H_2, H^-, collision-induced absorption by H_2, **Molecular line broadening**	H_2, H_3^+, **H_2O**, TiO, CO, CH, OH, YO, **VO, MgH, FeH, CaH, AlH, SiH, TiH, AlO, MgO, dust (Al_2O_3, $CaTiO_3$, $MgSiO_3$, Mg_2SiO_4, ZrO_2, Ti_2O_6, Ti_4O_7, Fe, Ni, Cu ...), Na I, Fe I,** *Mn I*, **ScI, Ni I,** *Ti I*, **Mg I, Al I, Cr I, K I, Si I, He I, Line broadening - alkali & molecular**	H_2, CO, HCN, CN, CH, CS, **CH_4, C_3, C_2H_2, AlH, dust, Molecular line broadening**

the question whether such stars are really primordial ones which have accreted some metals or are the results of the first supernovae explosions.
(7) At present many known ESPs are larger than Jupiter but orbit close to their star so they are strongly irradiated. Assuming these planets are gas giants, what is their chemical structure and thermal composition? Even more importantly, do they exhibit a clear spectral signature?
(8) Models of variable stars, e.g. Mira: present models underestimate the mass loss rates and these models are particularly sensitive to the input molecular data.

Our understanding of all these problems, and others, depends heavily on the improvement of atmospheric and evolutionary models. Advances in atmospheric modelling of LMS, BDs and ESPs have been slowed down by three main unresolved issues: (1) inaccurate and incomplete treatment for opacity; (2) the lack of an accurate equation of state; (3) inaccurate (by more than 50% at times) oscillator strengths of important atomic spectral markers.

3. Requirements for opacities, equation of state and line characteristics

The main sources of opacity for LMS, BD and ESP are open shell diatomics (such as TiO), polyatomic molecules (such as H_2O) and dust. Although most of the molecules that play an important role in the opacity of these objects have been known since the early 1930s, in the absence of detailed lists of transitions for them, it has been necessary to resort to average opacities such as the Just Overlapping Line Approximation, Straight Mean or Harmonic mean techniques, which approximate (by a continuum distribution) the absorption within a band or a predefined wavelength bin. While computationally

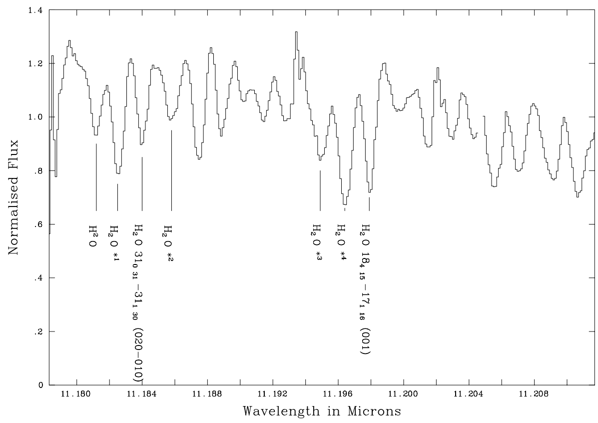

Fig. 3. Example of water line assignments in the mid-infrared spectrum of the cool giant BS337 (Davies et al. 2004). Some lines have been identified. Some lines have been identified as water lines but no quantum assignment has yet been done. Most assignments are blended transitions.

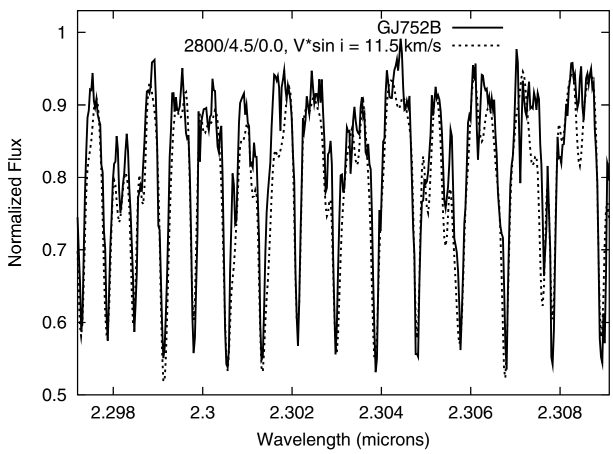

Fig. 4. This is an example from Jones et al. (2005) of the particularly good fits that can be obtained in spectral regions such as the K band where the dominant opacities, in this case CO and water, can well fit observational data.

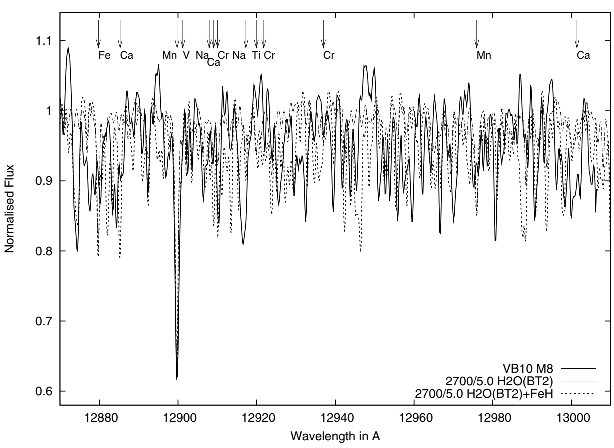

Fig. 5. The relatively poor fit of synthetic spectra to high resolution spectra in the J band region can be seen in this example plot for vB10 from Lyubchik et al. (in preparation).

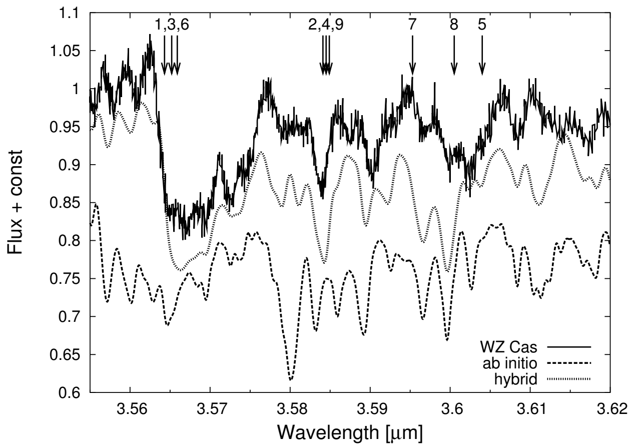

Fig. 6. The plot shows observed (WZ Cas) and synthetic spectrum computed with the old and improved linelist. Experimental HCN energy levels have been used in the improved linelist, to give far more accurate line frequencies. The experimental data is obviously limited to the lower energy bands, so there is no improvement in the high energy hot bands (Harris et al. 2006).

economical, they make the assumption that the rotational fine structure is smeared out, ie., the lines overlap without being saturated. Such conditions are never truly met even for the strongest bands of TiO and H_2O in the densest of the LMS atmospheres and these models tend to overestimate the resulting molecular blanketing by trapping photons that would otherwise have escaped from between the lines. A far more accurate account of molecular and atomic opacities in model atmospheres is achieved by applying an Opacity Sampling (OS) treatment of transition lists on a prescribed fine grid of wavelengths. However, even with great improvements in the treatment of opacities for some species (e.g., CO, TiO), we still lack accurate opacities for important absorbers such as H_2O and CH_4 (e.g., Fig. 2). Another strong source of opacity is the condensations of molecules and grains: the impact of condensation on the spectral distribution and atmospheres of LMS, BD and ESP is to gradually deplete the gas phase of Titanium, Iron, Vanadium and Oxygen. Models need to include both grain formation and grain opacities: present models have shown that the inclusion of opacities of corundum, enstatite and iron heat the photospheric layers and change the overall structure of the atmosphere. Yet the state of art dusty models are still coarse and better grain opacities which include equilibrium condensation abundances, effects of distribution of grain sizes and shape are needed.

The equation of state (EOS), i.e., the relations between the density and temperature of the material on the one hand and its pressure and internal energy, specific heats, etc, on the other hand is for most stars quite simple as most of the gas consists of Hydrogen and other light elements, and these have lost most of their electrons. However, in the case of LMS, non-ideal effects, such as Coulomb interactions become important. It is then necessary to use a better equation of state where all the relevant atoms and molecules are included and partition functions for all these species need to be accurately known. The development of a detailed EOS is necessary to calculate the occupation numbers needed for opacity calculations; for example, for ultracool dwarfs it is essential to have accurate abundances of species such as Deuterium since the Deuterium burning limit is currently defined as the separation between BDs and ESP. Hence, as most of the Deuterium would be locked in HDO, an accurate partition function for this species is desirable.

While atomic features make little difference to the opacity of these objects, they are extremely important spectral markers and potentially excellent diagnostics for effective temperature, metallicity and surface gravity. A further issue is line broadening. The strongest lines can be very broad owing to van der Waals pressure broadening due to the interaction between two different neutral particles. No exact method has yet been developed for the case of collisions of atoms and molecules with the molecular Hydrogen that dominates the atmospheres of BD and ESP. The production of reliable synthetic spectra thus also requires the use of complete linelists as well as a systematic theory of line broadening.

4. First steps to making sense of high resolution spectra

A crucial aspect of this work is to prioritise the many and complex theoretical uncertainties. Our method has been to compare the behaviour of synthetic spectra from existing model atmospheres with high quality, high resolution infrared spectra. In Lyubchik et al. (2004) we have prioritised our the measurement of atomic feature based on their strength in sunspot umbral and synthetic spectra from 1–2.5 μm. Following this programme of atomic line selection using the NIST and LUND facilities we have measured the strengths of Mn (Blackwell-Whitehead et al. 2005a,b) and Ti lines (Blackwell-Whitehead et al., to be submitted). Furthermore we have investigated other atoms. Al and Cr seem to be promising for our laboratory based studies, although it is probably too difficult to make suitable anodes for the measurement of Na and K. In the near future we will investigate the feasibility of measurements of Sc, Fe, Y and Lu.

While our atomic work continues in earnest it is also crucial to identify regions of the infrared spectra which may already be well fit by the existing generation of models. In general terms we find that fits at longer wavelengths are improved. For example in Fig. 3 and 4, the primary features can be identified as water and carbon monoxide. Whereas at shorter wavelengths it can be considerably more difficult to disentangle competing atomic and molecular species, e.g. Fig. 5. On the other hand it is comforting to realise that the features which can be well fitted by the models are the Mn features for which we have measured oscillator strengths. While it is crucial for us to focus on such detailed line-by-line analyses we must also look more hollistically at all the details of our atmospheric models and spectral syntheses. To this end a number of other key areas of PoSSO research are now briefly mentioned.

5. A variety of key PoSSO results

- Molecular line lists for H_20 (Barber et al. 2006), HCN/HNC (e.g., Fig. 6 by Harris et al. 2006), ${H_3}^+$, TiO, VO and CrH (Pavlenko et al. 2005a) are near completion.
- A unified theory of collisional line profiles has been applied for the evaluation of absorption profiles of alkalis lines perturbed by Helium and molecular Hydrogen (Allard, Allard & Kielkopf 2005).
- Previous computations of low-temperature Rosseland and Planck mean opacities have been updated and expanded. The new computations include a more complete equation of state (EOS) with more grain species and updated optical constants. Grains are now explicitly included in thermal equilibrium in the EOS calculation, which allows for a much wider range of grain compositions to be accurately included than was previously the case (e.g., Ferguson et al. 2005).
- A grid of synthetic spectra has been computed exploring the day-night temperature difference and phase-dependent flux densities experienced by close-orbiting giant extrasolar planets (Barman, Hauschildt & Allard 2005).
- Resolution of the low-lithium abundance in prototype late-type young brown dwarf LP944-20 (Pavlenko et al. 2005b).
- Spectra have been calculated for HeH^+ and its importance for 3500K metal-poor stars has been determined (e.g., Engel et al. 2005).
- The effect of the electron donor H^{3+} on the pre-main-sequence and main-sequence evolution of low-mass, zero-metallicity stars has been found to be rather significant (e.g., Harris et al. 2004).
- The model atmospheres for AGB stars which combine time-dependent dynamics and frequency-dependent radiative transfer have been investigated. This allows us to take both the effects of pulsation (shock waves, stellar winds) and the complex influence of molecular opacities into account (e.g., Hofner et al. 2003).
- We present the first line-by-line computation of the absorption coefficient of methane aimed at describing the high temperature opacities of the gas-phase. Our preliminary data include 5 million lines with an accuracy in the line position of 1 cm^{-1} for all vibrations and rotational values up to J = 65, and with an accuracy of approximately 10% in the intensity (e.g., Borysow et al. 2003).
- We are engaged in an ongoing programme of 3D simulations of convection-related stellar micro-variability and its influence on stellar line formation (e.g., Ludwig 2005; Steffen, Freytag & Ludwig 2005).
- Prioritised atomic lines, e.g., http://star.herts.ac.uk/∼hraj/spectratlas (Lyubchik et al. 2004).

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References

Allard, N.F., Allard, F., Kielkopf, J.F.: 2005, A&A 440, 1195
Barber, R.J., Tennyson, J., Lynas-Gray, A.E.: 2006, MNRAS, in preparation
Barman, T.S., Hauschildt, P.H., Allard, F.: 2005, astro-ph/0507136
Blackwell-Whitehead, R., Xu, H.L., Pickering, J.C., Nave, G., Lundberg, H.: 2005a, MNRAS 361, 1281
Blackwell-Whitehead, R., Pickering, J.C., Pearse, O., Nave, G.: 2005b, ApJ 157, 402
Borysow, A., Champion, J.P., Jorgsen, U.G., Wenger, C.: 2003, ASP Conf. Ser. 288, 352
Butler, R.P., Marcy, G.W.: 1996, ApJ 464, L153
Charbonneau, D., Brown, T.M., Latham, D.W., Mayor, M.: 2000, ApJ 529, L45
Davies, S., Viti, S., Jones, H.R.A., Tennyson, J., Miller S.: 2004, UKIRT Newsletter 14
Engel, E.A., Doss, N., Harris, G., Tennyson, J.: 2005, MNRAS 357, 471
Ferguson, J.W., Alexander, D.R., Allard, F., Barman, T., Bodnarik, J.G., Hauschildt, P.H., Heffner-Wong, A., Tamanai, A.: 2005, ApJ 623, 585
Harris, G.J., Lynas-Gray, A.E., Miller, S., Tennyson, J.: 2004, ApJ 600, 1025
Harris, G.J., Kaminsky, B., Tennyson, J., Pavlenko, Y.V., Jones, H.R.A.: 2006, MNRAS, submitted
Hayashi, C.: 1961, PASJ 13, 450
Henry, G., Marcy, G.W., Butler, R.P., Vogt, S.S.: 2000, ApJ 529, L41
Hofner, S., Gautschy-Loidl, R., Aringer, B., Jorgensen, U.G.: 2003, A&A 399, 589
Jones, H.R.A., Longmore, A.J., Jameson, R.F., Mountain, C.M.: 1994, MNRAS 267, 413
Jones, H.R.A., Pavlenko, Y., Viti, S., Barber, R.J., Yakovina, L.A., Pinfield, D., Tennyson, J.: 2005, MNRAS 358, 105
Kumar, S.S.: 1962, AJ 67, 579
Ludwig, H.-G.: 2005, astro-ph/0509441
Lyubchik, Y., Jones, H.R.A., Pavlenko, Y.V., Viti, S., Pickering, J.C., Blackwell-Whitehead, R.: 2004, A&A 416, 655
Mayor, M., Queloz, D.: 1995, Nature 378, 355
Nakajima, T., Oppenheimer, B.R., Kulkarni, S.R., Golimowski, D.A., Matthews, K., Durrance, S.T.: 1995, Nature 378, 463
Oppenheimer, B.: 1999, PhD, California Inst. of Technology
Pavlenko, Y.V., Jones, H.R.A., Tennyson, J., Barber, R.J., Martín, E.L.: 2005a, A&A, in preparation
Pavlenko, Y.V., Jones, H.R.A., Martín, E.L., Guenther, E., Kenworthy, M.: 2005b, MNRAS, submitted
Rebolo, R., Zapatero Osorio, M.R., Martín, E.L.: 1995, Nature 377, 129
Steffen, M., Freytag, B., Ludwig, H.-G.: 2005, astro-ph/0509464
Tamura, M., Itoh, Y., Oasa, Y., Nakajima, T.: 1998, Sci 282, 1095
Viti, S., Jones, H.R.A., Maxted, P., Tennyson, J.: 2002, MNRAS 329, 290