CONFERENCES AND SYMPOSIA

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Joint scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences and the Joint Physical Society of the Russian Federation (30 January 2002)

A joint scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (RAS) and the Joint Physical Society of the Russian Federation was held on 30 January 2002 in the conference-hall of the P N Lebedev Physics Institute, RAS. The following reports were presented in the session:

(1) **Balega Yu Yu** (Special Astrophysical Observatory, RAS, Nizhniĭ Arkhyz, Karachaevo-Cherkessia, Russia) "Brown dwarfs: substars without nuclear reactions";

(2) **Efremov Yu N** (P K Sternberg Astronomical Institute, M V Lomonosov Moscow State University, Moscow) "Star formation bursts in normal galaxies";

(3) **Oraevskiĭ V N** (Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of RAS, Troitsk), **Sobel'man I I, Zhitnik I A** (P N Lebedev Physical Institute of RAS, Moscow), **Kuznetsov V D** (Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of RAS, Troitsk, Moscow Region) "Comprehensive solar studies by CORONAS-F satellite: new results";

(4) **Cherepashchuk A M** (P K Sternberg Astronomical Institute, M V Lomonosov Moscow State University, Moscow) "Wolf – Rayet stars and relativistic objects";

(5) **Tsvetkov D Yu** (P K Sternberg Astronomical Institute, M V Lomonosov Moscow State University, Moscow) "Type Ib/c supernovae: new observational data".

Summaries of four of the papers (except for paper 2) are given below.

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Brown dwarfs: substars without nuclear reactions

Yu Yu Balega

Definition. In 1963, Kumar [1] showed that the hydrogen burning in a stellar core stops below some mass limit and the gravitational contraction of the object is balanced by the degenerate electron gas. The equilibrium of thermal pressure and quantum electron pressure implies a limiting mass of ~ 0.072 solar mass ($M_\odot$). The limiting mass is somewhat higher, up to $\sim 0.09\,M_\odot$, for objects in which the heavy element abundance is significantly below the solar value. Substellar objects which are not massive enough to sustain the stable hydrogen burning in the core are called brown dwarfs (BDs). BDs are failed stars. How can one discover such objects? How many of them reside in our Galaxy and how much do they contribute to the hidden mass? Is there a continuous transition from the low-mass substellar objects to giant planets? Do their formation mechanisms differ from ordinary stars? Astronomers have been interested in these and many other questions for several decades.

The internal structure of BDs. BD interior consists of fully ionized hydrogen-helium plasma. The degeneracy parameter $\psi = kT/kT_{\mathrm{F}}$, where T_{F} is the Fermi temperature, is very small for very low-mass stars and BDs and varies within the range from 2 to 0.05, so to describe their internal state the thermodynamical properties of partially degenerate electron gas should be taken into account. Recall that $\psi \to \infty$ corresponds to a classical gas (the Maxwell – Boltzmann limit) and $\psi \to 0$ means total degeneracy. The equation of state for dense astrophysical objects was first proposed by Salpeter [2]. Figure 1 illustrates the central characteristics of low-mass stars and substellar objects in the mass range from Jupiter to the Sun. In constructing these relations, the solar abundance of heavy elements and an age of 5×10^9 years were assumed. For stars with a mass exceeding $\sim 0.4\,M_\odot$, the central radiative core grows with increasing mass, which is accompanied by a pressure and density increase. However, below $\sim 0.35\,M_\odot$ the stellar interiors become fully convective and, since the gas still remains in the classical regime ($\psi \geqslant 1$), the mass increases in proportion to the stellar radius R, and the central density ρ_{c} decreases with mass as M^{-2}. Below the hydrogen burning limit, electron degeneracy starts dominating, so $M \sim R^{-3}$ and the density increases again with increasing mass. The mass-radius dependence $R \sim M^{-1/3}$, as for white dwarfs, is established at full degeneracy, however for partial degeneracy the dependence has a smaller slope — the BD radius weakly depends on mass. With the solar age and metallicity, a BD has a radius like Jupiter (0.1 $R_\odot$).

Figure 2 shows how the temperature in the center of a low-mass object varies with time. A detailed review of the physical, mechanical, and thermal properties of very low-mass stars and BDs has been written by Chabrier and Baraffe [3].

By definition, no nuclear energy is generated in the substellar regime. The entire BD evolution is determined by the internal energy released during the compression. Even when the degeneracy becomes important, the BD continues contracting slowly. The BD contraction time is comparable with the Hubble time.

The main energy transfer mechanism in BDs, like in very low-mass stars, is convection whose speed is $v_{\mathrm{conv}} \sim 1$ m s^{-1}. However, the convection can be largely suppressed by rapid rotation of the dwarf. Observations indicated that in some objects the rotation can reach 50 – 80 km s^{-1}, which cor-

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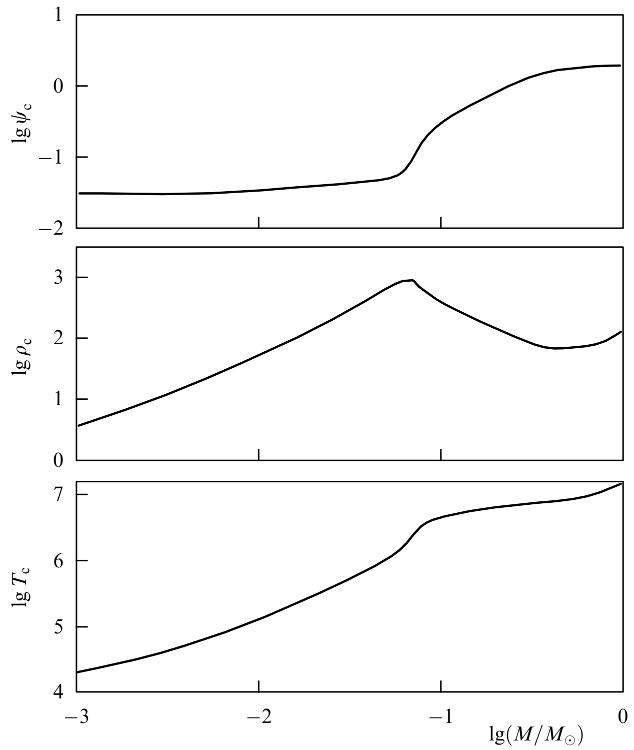

Figure 1. Degeneracy parameter ψ, central density ρ_c, and central temperature T_c for low-mass stars and BDs with solar abundance of heavy elements and an age of 5 billion years.

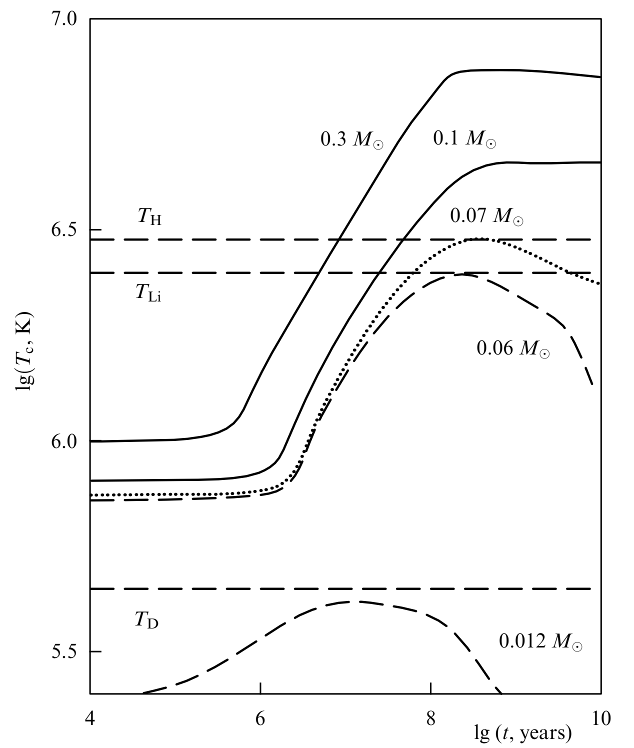

Figure 2. Central temperature T_c as a function of age for different masses. T_H, T_{Li}, and T_D denote the burning temperature of hydrogen, lithium, and deuterium, respectively. (According to Ref. [3].)

responds to an angular velocity of $\Omega \sim 5 \times 10^{-4}$ rad s^{-1} at the characteristic radius 0.1 $R_\odot$. With such a rotation, the Rossby number $R_0 = v_{conv}/\Omega l \sim 10^{-3}$, where l is the mixing length, and the convection can be fully suppressed. In such rapidly rotating BDs, other energy transfer mechanisms should also exist, such as meridional circulation, turbulence, and thermal conductivity. Inside BDs, on cooling, the energy flux due to thermal conductivity can exceed the convective flux.

Atmospheres of BDs. Modeling BD atmospheres is a complex problem because molecular absorption (millions of spectral lines) should be properly calculated and the presence of condensates should be taken into account. Also important is the fact that the BD luminosity is $10^{-2} - 10^{-5}$ times the solar one $L_\odot$, so their spectral classification in extremely difficult.

At surface temperatures below $T_{eff} \leqslant 4000$ K, most hydrogen is bound into H_2 molecules and carbon into CO. The excess of oxygen is bound into TiO, VO, OH, and H_2O. For an object with a mass of $\sim 0.075\, M_\odot$ the gravity acceleration $g = Gm/R^2$ on the surface is $\log g \sim 5.5$, the pressure is $P_{ph} \sim 10$ bar, the density is $\rho_{ph} \sim 10^{-4}$ g cm^{-3}. Under such conditions, absorptions due to molecular collisions play an important role in the spectrum.

Figure 3 shows the sequence of the near infrared (IR) spectra of dwarf stars from spectral class M to BDs (the UKIRT telescope data; Jones et al. [4] for M-dwarfs, Geballe et al. [5] for Gl 229B). In the transition from red dwarfs to BDs, the water bands notably strengthen and broad bands of methane (CH_4) appear. Clouds of Al_2O_3 (corundum), iron, $CaTiO_3$, $MgSiO_3$, and Mg_2SiO_4 form in the atmosphere, which can lead to the appearance of the greenhouse effect in the photospheric layers. In the visible part of the spectrum, at temperatures below 200 K the alkali metal absorption lines (Na I, K I, Rb I, Cs I) appear and the molecular lines of TiO and VO, typical for red dwarfs, almost completely disappear. The absorption line K I at 7700 Å transforms into a broad depression.

Modeling atmospheres of cold dwarfs is a complex nonlinear problem. The '3000 K barrier' was overcome only 10 years ago [6], when numerous molecular lines of hydrides were included into the model in addition to the dominating opacity due to TiO and H_2O. Nonetheless, the problem of modeling the IR spectrum remains, mainly because of water bands. There are theoretical lists of the H_2O lines; for example, Miller et al. [7] provide a list of 6 million lines, Partridge and Schwenke [8] — of 300 million lines; however, so far none of

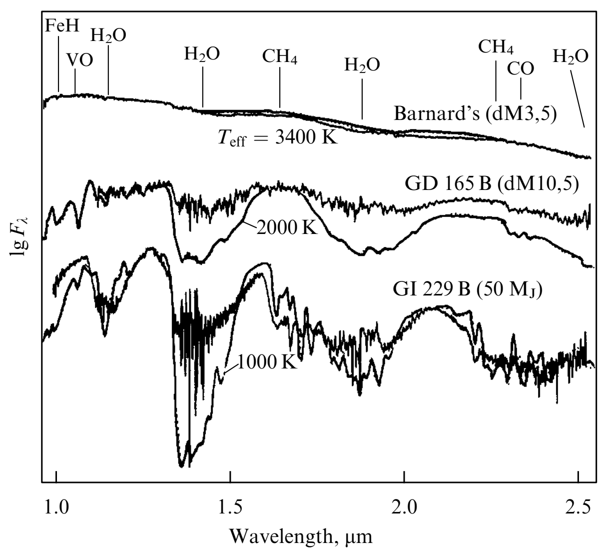

Figure 3. Change in the IR spectrum from red dwarfs to BDs. Models are given for $T_{eff} = 3400$ K (Barnard star), 2000 K, and 1000 K.

them has been capable of describing the observed water vapor bands in late stars and BDs. Modern models do not properly take into account the condensation of molecules into grains either. A detailed review of the atmosphere models of very low-mass stars and BDs has been made by Allard et al. [9].

The search for BDs. There are several possible ways of searching for BDs. At first, one can look for very old BDs among objects with a temperature below 2000 K immediately close to the Sun. This is a difficult problem, since, by definition, BDs never reach thermal equilibrium, and the luminosity of BDs formed at early stages of the Galaxy evolution drops to very small values ($L \sim 1/t$). At second, it is possible to search for young BDs in young stellar clusters. The luminosity of those BDs will be higher so they can be more easily detected, however it will be always difficult to separate them from red dwarfs. Finally, it is possible to discover BDs dynamically by measuring their mass from the orbits of multiple BD systems or star — BD pairs.

The main criterion in the BD searches is the presence of traces of Li in the spectrum. The primordial lithium enters in the proportion $1 : 10^9$ H in the formation of stars from the times of the 'Big Bang'. Inside stars, at temperatures $T \sim 2 \times 10^6$ K lithium is rapidly destroyed in collisions with protons: $^7\mathrm{Li} + \mathrm{p} \rightarrow 2\,^4\mathrm{He}$. Red dwarfs are fully convective, so Li is mixed up and burnt away. However, at masses of substars $M \leqslant 0.07\ M_{\odot}$ the temperature does not reach such values and ^{7}Li is conserved (Fig. 4). It can be discovered by a doublet at the wavelength of 6708 Å. The lithium test was first proposed by Rebolo et al. [10] and Pavlenko et al. [11].

The first BD candidate was discovered in 1995 in the young stellar cluster Pleiades (aged 100 million years) with the 10-meter W. Keck telescope: the signatures of Li were found by Basri et al. [12] in the spectrum of object PPL15. However, the PPL15 mass is close to the hydrogen burning limit in the core, so it is not excluded that PPL15 is a late M-dwarf. Any object with a luminosity below that of PPL15 must be a BD. So far, several BDs have been discovered by astronomers in the Pleiades. Similar searches for BDs using large ground-based telescopes were carried out in other young stellar clusters.

A very weak companion of star Gl 229 proved to be the first reliably confirmed BD. It was discovered in the K-filter (2.2 μm) by the adaptive-optics coronograph on 1.5-meter reflector at Palomar Observatory, USA [13]. Its stellar K-magnitude is $M_{\mathrm{K}} = 15.6$ (hundreds times lower than PPL15), and the mass is by far lower than the threshold value, of only $0.03 - 0.04\ M_{\odot}$. Gl 229B is one of the coldest BDs, its surface temperature is about 900 K. Somewhat later, even a colder object was discovered, the companion to star Gl570ABC with $T_{\mathrm{eff}} \sim 750$ K. Its luminosity is 3×10^5 times lower the Sun. In the spectra of these objects, broad bands of CH_4 and H_2O dominate. Hundreds of new BDs were found in surveys of field stars using special telescopes equipped with matrix detectors of the visible and IR light.

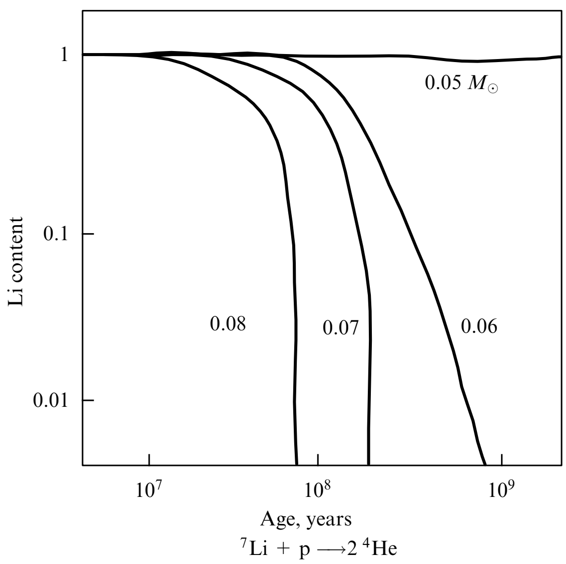

Figure 4. Change in the lithium content with age for different masses.

At present, spectra of a great number of BDs have been obtained, which allows their spectral classification. Martin [14] and Kirkpatrick et al. [15] proposed classifying BDs in the new spectral classes L and T. The spectral scale is not yet established for M-dwarfs, but it is accepted that the lower temperature limit for them is $T_{\mathrm{eff}} = 2000$ K. The L-class stars are below this limit, with each subsequent subclass being 100 K colder than the previous. Object Gl 229B represents the spectral class T of even colder methane stars. The methane bands in their spectra are observed at 3.5 μm already at a temperature of $T_{\mathrm{eff}} = 1600$ K, and at 2 μm — at $T_{\mathrm{eff}} = 1200$ K. The temperature scale for the T-dwarfs is not finally established, as the spectral energy distribution is determined by the dust content. By color they may appear bluer than the L-dwarfs because CH_4 suppresses the depression in the K-band.

In analogy with the Li-test, one can apply the test for the presence of deuterium (D is destroyed in stars before Li). Such a test is applicable for objects with even lower masses or very young BDs. The burning of D at $M \geqslant 0.013\ M_{\odot}$ occurs at the initial evolutionary stages and lasts for $\sim 10^6 - 10^8$ years. Objects with a smaller mass can not burn deuterium, so it is natural to define the mass $0.013\ M_{\odot}$ as the boundary between BDs and giant planets.

BDs in multiple systems. It is commonly accepted that stars are born in multiple systems and groups. The fragmentation is the main formation mechanism of multiple stars in the collapse of the protostellar gas-dust disk. Detecting BDs in systems of ordinary stars could be the cornerstone in the discussion of their nature. The first BD, a companion to white dwarf GD 165, was discovered by astronomers in surveying hundreds of white dwarfs. One interesting multiple BD system was studied on the 6-meter telescope BTA of the Special Astrophysical Observatory of RAS [16]. IR observations of Gl569B by interferometry methods allowed the image with diffraction resolution to be recovered (Fig. 5) and the total dynamical mass of the object $0.14\ M_{\odot}$ to be determined from the orbital motion. It is not excluded that Gl 569B consists of three almost identical components with a mass of about $0.045\ M_{\odot}$ (the brighter component is a close pair which is not resolved by the telescope). We used the kinematics of the object to establish that Gl 569B belongs to a moving group of Ursa Majorae and its age is about 300 million years.

It is extremely difficult to discover a BD in pair with a late-type G – M star directly on the telescope image due to a large brightness difference. But very low-mass components can be found by Doppler shift of the radial velocities of the stars. Spectroscopic surveys of velocities of stars near the Sun yielded a somewhat unexpected result: with the comparatively large number of planetary-mass objects detected, the number of BDs in systems with G – M stars proved to be small ($< 1\%$). We note for comparison that the fraction of binary red dwarfs amounts to 50%. Possibly, this is evidence for

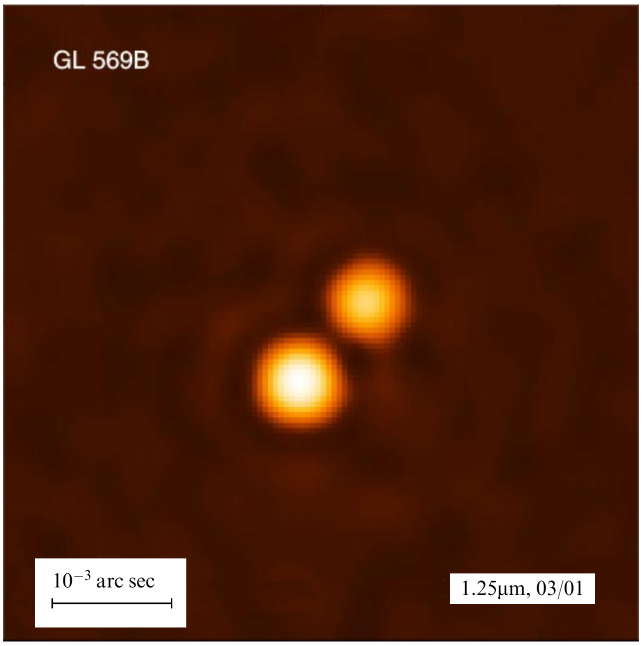

Figure 5. The image of the system of dwarfs Gl 569B obtained on the BTA telescope using IR speckle-interferometry at 1.3 μm. The distance between the components is $0.089''$ ($\approx$ 1 a.u.).

different formation mechanisms of stars and very low-mass substellar objects.

The number of BDs and the mass function. Now more than half the area of the Pleiades cluster has been searched for the presence of BDs. The BDs turn out to form a numerous population containing up to 10% of the total cluster mass. The survey of the field stars in the Northern hemisphere by the 2MASS telescope at the wavelength 2 μm, which has already revealed more than 200 new BDs, allowed astronomers to conclude that the mass function of low-mass objects has the form $dN/dM = M^{\alpha}$ with $2 > \alpha > 1$. If $\alpha \approx 1.3$, the local density of BDs with $0.075 > M/M_{\odot} > 0.01$ is about 0.1 system per pc^3, or $\sim 0.005\ M_{\odot}\ pc^{-3}$. This means that BDs are as numerous as stars in the Galaxy disk, but they contribute not more than 10% of the total mass. The estimate of the number of T-dwarfs with surface temperatures below 1000 K gives the same order of magnitude. The microlensing observations of stars in the direction of the central parts of the Galaxy also suggest that BDs contribute less than 10% of the stellar mass. Therefore, substellar objects may be our most wide-spread neighbors, however the possibility that they are responsible for the dark matter in the Galaxy is totally excluded (this would require $\alpha > 3$).

Formation of BDs. There are three possible BD formation mechanisms. (a) BDs result from the collapse of a hierarchically structured protostellar cloud, like stars with larger masses. The hierarchical cloud model always produces the Salpeter mass function. Calculations show that in cold clouds ($T \sim 3$ K), up to 50% of the mass and up to 90% of the number of objects will be BDs. (b) BDs are formed as a result of gravitational instability of a gas-dust disk around a forming star. This model somewhat contradicts the small fraction of the observed BDs — companions to ordinary stars. (c) BDs originate from the ejection of stellar embryos from the star forming region due to momentum and energy exchanges. For an embryo to have no time to acquire mass, the characteristic time before the ejection must be very short, $\sim 10^3 - 10^4$ years. However, recent measurements of the BD radial velocity dispersion in the dark molecular cloud in Chameleon indicated that it does not differ from the velocities of the surrounding stars and gas and, hence, no escape velocities are observed.

Problems. The immediate problems of the BD studies include the determination of the BD cooling curves to specify the atmosphere models, the determination of the mass of individual interacting systems, the mass function specification to determine the BD contribution to the dark matter in the Galaxy. Ground-based possibilities of BD observations are very limited. New space experiments like IRIS, SIRTF, and NASA Planet Finder may discover cold methane T-dwarfs at distances ~ 200 pc, i.e. across the entire galactic disk. Objects with a mass of $\sim 0.01\ M_{\odot}$ can be observed up to a distance of 50 pc.

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Comprehensive solar studies by CORONAS-F satellite: new results

V N Oraevskiĭ, I I Sobel'man,
I A Zhitnik, V D Kuznetsov

1. The CORONAS program and CORONAS-F project

The paper presents the results of comprehensive studies of solar activity by the CORONAS-F satellite.