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Low luminosity stars: How no(w) brown dwarfs?

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sensory processing (for example, the centre-surround organization of retinal ganglion cells), but it would affect whatever parameters are laid out along the surface coordinates of a particular cortical area. This kind of hypothesis can be tested when the analytical approaches now being applied succesfully in area 17 are extended to other parts of the cerebral cortex. ☐

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## 100 years ago
### THE SUN AND STARS
#### The Chromosphere

In what has gone before we have been chiefly occupied with a discussion of the various chemical materials which we can trace in those cavities in the photosphere which we call spots. We have now to begin the consideration of the chemical materials which can be traced in that solar envelope which lies immediately over the photosphere, I mean the chromosphere: so that eventually we may endeavour to make a comparison between the chemical materials in the spots and in the chromosphere, which are supposed to lie, and which in fact really do lie, at about the same height in the solar atmosphere, with, however, the enormous difference that we know the spots are caused by the descent of materials coming down from above, and we do not know at present that that is true with regard to the substances in the chromosphere.
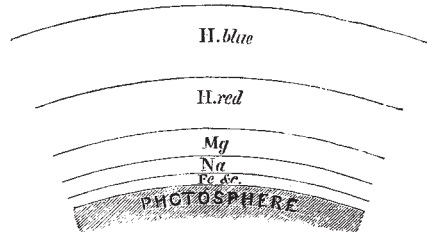


Early hypothesis of the arrangement of materials in the Sun's atmosphere. H = hydrogen; Mg = Magnesium; Na = sodium; Fe, & c. = iron and the other elements of high atomic weight.
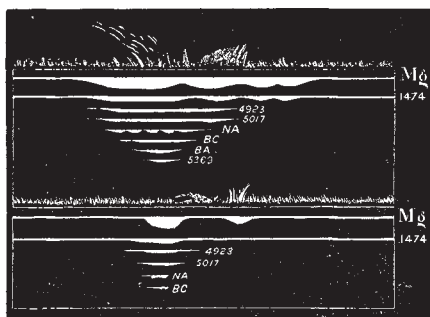


Welling up of vapours

Now, the chromosphere we will take roughly, as it varies in height from year to year, and from latitude to latitude, to be between 5000 and 10,000 miles high. It is not only bright at the bottom — so bright, very often, that in eclipses, when the bottom is seen, observers imagine that the sun has reappeared — but it is exquisitely coloured at the top, and colours very often being scarlet, crimson, green, yellow, and so on. As ordinarily observed, the simple chromosphere varies very considerably.

From *Nature* **33** 499, 25 March 1886.

## Low-luminosity stars

# How no(w) brown dwarfs?

*from Virginia Trimble*

WHOLE careers and industries are built on extremes — the highest jump, the oldest fossil, the fastest horse. Thus it is perhaps not surprising that astronomers should, now and again, ask themselves which is the smallest star and does it differ significantly from the largest planet? The current best answers are van Biesbroeck 8B (vB8B) and yes, according to speakers at a workshop* last autumn.

The difference between stars and planets is at least as much in how the objects form as in their present energy sources, and vB8B falls cleanly in the 'star' class, although contraction may be contributing as much to its luminosity as nuclear reactions do. I shall return shortly to the third big question addressed at the workshop: are there enough faint stars to affect estimates of the local mass density (one aspect of the widespread 'missing mass' problem)? To this, the democratically chosen answer was a resounding 'maybe', but the situation looks a good deal more promising for small stars than it did a year or two ago.

David C. Black (NASA/Ames) drew a sharp line between small stellar companions and planets[1]. Stars form by fragmentation of a gas cloud without significant dissipation or chemical fractionation. Planets result when dissipation produces a disk around a single proto-star, within which bodies condense whose chemical composition and mass depend on distance from the centre of the disk. Alan P. Boss (Carnegie Institution, Washington) provided confirming evidence for this distinction. He has followed numerically the collapse and fragmentation of gas clouds of varying temperature and rotation rate until the fragments are so small that thermal support lets them contract slowly into single stars rather than breaking up further. No fragments smaller than $0.02-0.05$ $M_\odot$ $(20-50$ Jupiter masses, $M_j)$ ever formed, requiring a separate origin for planet-sized bodies. Most of the effects neglected in the calculation will tend to raise the limiting mass slightly. Boss and Hans Zinnecker (Royal Observatory, Edinburgh) both noted the main exception. Less dust lowers the limit by contributing less capacity, leaving open the possibility of still smaller stars within the metal-poor first generation, some of which may linger in the halo of our Galaxy.

None of the smallest fragments will ever burn hydrogen. This requires a mass $M \geqslant$

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* 1985 George Mason workshop on Brown Dwarfs, held at the George Mason University, Fairfax, Virginia 22030, USA from 14-15 October 1985.

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$0.08$ $M_\odot$ and provides the traditional definition of 'real' stars, presenting us with the problem of what to call the smaller objects. Jill Tarter (University of California at Berkeley) put forward a strong case for the continued use of the folk name 'brown dwarfs', on the grounds that objects whose emission spectra we cannot even roughly predict should properly be called by a name that is not, spectroscopically speaking, a colour.

Deciding whether there are enough brown dwarfs to contribute appreciable local mass density is much more difficult. The task has several pieces: (1) identifying faint-star candidates and making sure there are no systematic biases against detection; (2) acquisition of enough data (colours, distances) or accurate enough model atmospheres to determine absolute brightnesses or effective temperatures for the candidates; (3) converting these to masses; and (4) drawing plausible extrapolation curves without violating other known limits.

Identifying candidates is a struggle in itself, many projects yielding only upper limits. Bruce Campbell (Dominion Astrophysical Observatory, British Columbia) and Geoffrey Marcy (San Francisco State University) reported searches for variable stellar radial velocities that might reflect the gravitational influence of invisible companions. Both searches rediscovered known binaries, but the former ruled out companions bigger than $1-3$ $M_j$ with orbit periods less than 5 years for all half-dozen stars examined, and the latter excluded companions above $7-50$ $M_j$ with periods $\leqslant 1$ year for all but one of 65 stars. The period limits are too short to tell us much about massive planets, but a possible class of brown-dwarf companions must be rare. Marcy's new find orbits Gliese 623 (CC 986) with a 2.1-year period and is probably $0.05-0.08$ $M_\odot$. Curiously, Gliese 623 was already known, from astrometric and infrared studies, also to have a slightly more massive companion in a 3.7-year, non-coplanar orbit. An investigation of the stable lifetime of this system would be interesting.

Other non-detections include single brown dwarfs and companions to nearby white dwarfs in the Infrared Astronomy Satellite (IRAS) database reported by Frank J. Low (University of Arizona) and Harry L. Shipman (University of Delaware) and companions to nearby main sequence stars and white dwarfs in images recorded with the Infrared Telescope Facility (IRTF) by M.F. Skrutskie (Cornell University) and C. Krishna Kumar

(Howard University). Because faint hydrogen burners, brown dwarfs and Jupiters all have radii near a tenth that of the Sun, these infrared searches essentially constrain brightness temperatures of hypothetical companions to be less than 2,000–2,500 K at the wavelength of observation (2–3 μm at the IRTF; 12 μm for IRAS). The uncertainties in turning these into luminosity and mass limits make interpretation difficult, except that the IRAS database should contain only about one identifiable brown dwarf even if such stars make up all the local missing mass and radiate like black bodies. Finally, Patricia C. Boeshaar (Rider College) discussed the status of a continuing search for faint dwarfs and subdwarfs based on multicolour (J,R,I) charge-coupled device images. So far, seven objects have turned up that fit on the bottom end of the subdwarf (low metal abundance) hydrogen-burning sequence, but no very red candidates have appeared.

Still, faint stars do exist. Lists shown by Ronald Probst (Kitt Peak National Observatory), James Liebert (University of Arizona) and Conard Dahn (US Naval Observatory) included at least 16 with visual magnitude $M_v = 16$–$20$, found, in most cases, by astrometry or in proper motion surveys and confirmed by measured distances and infrared fluxes (see figure). Most have the large velocities characteristic of old stars ($> 10^9$ years), and so must be hydrogen burners. A few seem to be young and could be contracting, cooling brown dwarfs.

Going still fainter, Robert S. Harrington (US Naval Observatory) has found eight astrometric binaries whose orbit solutions permit two kinds of companions, the comparable and the negligible. The former will have masses $\geq 0.08 \ M_\odot$ like their primaries and should be detectable infrared sources; the latter range downwards from 0.05 to 0.01 $M_\odot$ and should be very faint. Five of these have been examined by Donald W. McCarthy Jr (University of Arizona) as part of a continuing infrared speckle program that has already confirmed other astronometric companions as among the faintest stars. Four could not be seen, supporting the low-mass, brown-dwarf alternative. The detected fifth is vB8B, whose companion[2], with a 1.1–2.2 μm colour temperature of 1,360 K and luminosity $L = 3 \times 10^{-5} L_\odot$, is the coolest, faintest star known. It is part of a small stellar group whose dynamical age exceeds $2 \times 10^9$ years and so is almost certainly a hydrogen burner.

The greatest surprise among the faint-star searches came from M.R.S. Hawkins (UK Schmidt and Telescope Unit). His repeat of an earlier, rather discouraging search[3,4] found 13 stars, rather than only 2, in the reddest bins, apparently because it went a bit deeper in the V colour band. Both his raw data and their transforma-

tion to absolute visual magnitude show a luminosity function that flattens off, begins to drop, but then rises again below $M_v = +16$. The 13 stars concerned have quite a low velocity dispersion, and Hawkins considers it possible that a new, young population of brown dwarfs is beginning to show up. The stars have been placed on a charge-coupled device parallax program for confirmation of their distances. Boeshaar expressed the opinon that these new counts are strictly inconsistent with her results, but given that the two projects
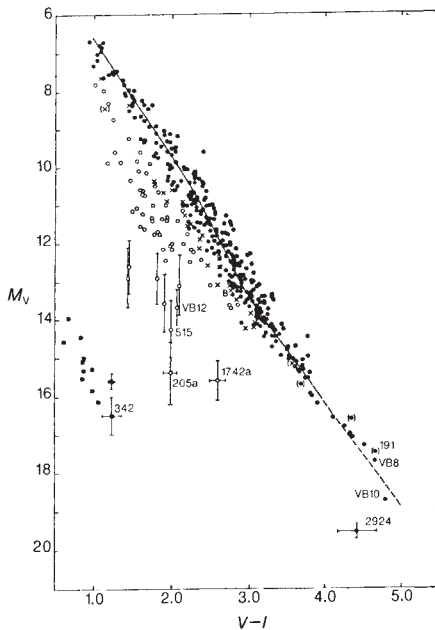


Hertzsprung–Russell (colour–magnitude) $(V–I)$ diagram of the nearby faint stars (C. Dahn and J. Liebert, personal communication). A clear, although sparsely populated, main sequence extends several magnitudes below $M_v = +16$. Some well-known stars are labelled, including vB8B. ●, Disk dwarfs; x, mild subdwarfs; o, subdwarfs; ■, degenerates.

used slightly different colour bands and that neither presented completely uninterpreted numbers of images, many participants suspected that the two could be reconciled in the direction of a luminosity function that first drops and then rises again.

The increased number of faint candidates combines with several theoretical developments to raise once again the possibility that brown dwarfs may comprise all or most of the local (disk and/or halo) dark matter. First, the transformation from a brightness temperature to a luminosity is not entirely straightforward. Below 2,500 K, molecules become important and dust grains form, gradually raising the opacity, but also making it a very non-uniform function of wavelength. For instance, the flux in the frequently used wavelength band R is seen to be as much as 2.9 mag less than that of a black body of the same total luminosity among known faint stars, according to Probst. Thus some searches may still not be looking

quite faint enough, and we may be assigning wrong brightnesses to things we do find.

Second, clouds of grains will eventually merge to form a cloud deck, with photons reaching us only from the cool zones above it. This can happen rapidly enough, according to David J. Stevenson (California Institute of Technology) to cause a discontinuity in the evolution of brown dwarfs, in which they drop quickly from $\geq$ 2,000 to about 1,300 K and then linger there for half a billion years or more while the trapped energy gradually leaks out. The corresponding luminosity is about that of vB8B ($3 \times 10^{-5} L_\odot$) which may, therefore, be in this plateau phase. The absence of slightly warmer objects in assorted searches would not be surprising, given this discontinuous evolution.

Finally, the simple power law commonly used for transformation from luminosity to mass turns out to underestimate severely the number of low-mass objects needed to account for a given luminosity distribution, $N(L)$. Francesca D'Antona (Osservatorio Astronomico di Roma) showed a new set of low-mass models[5] that incorporate molecular and dust opacity as well as exact equations of state for partially degenerate material that burns hydrogen out of equilibrium. The main surprise is a great stretching of the main sequence down to low luminosities. This results from a class of transition objects of 0.07–0.08 $M_\odot$ that never quite burn hydrogen vigorously enough to stop contracting, but do have their contraction timescales stretched out to billions of years by the nuclear contribution. Thus, a very narrow mass range provides most of the stellar population over a wide luminosity range, $10^{-3}$–$10^{-5} L_\odot$. The star vB8B falls in this range and is arguably such a transition object, of considerable age, and with a mass ($\sim 0.075 \ M_\odot$) near the upper end of the range permitted by the astrometric orbit.

Given the new models, the small number of known, faint stars implies a distribution of stellar masses, $N(M)$, that is at least flat or, more likely, still rising towards the brown-dwarf range. The high mass-to-light ratio of clusters of galaxies may still require massive theoryons, but the local problem begins to look much simpler, with ordinary faint stars, brown dwarfs and large planets as a possible solution. □

1. Black, D.C. & Levy, E.H. Science (submitted).
2. McCarthy, D.W., Probst, R. & Low, F. Astrophys. J. 290, L9 (1985).
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4. Reid, N. & Gilmore, G. Mon. Not. R. astr. Soc. 201, 73 (1982).
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