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Searches for brown dwarfs

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Abstract

This review attempts a brief summary of the numerous and diverse searches for the so-called brown dwarfs, substellar objects having masses between giant planets and the lowest mass M dwarf stars.

Cette revue donne un bref aperçu de l'état actuel des diverses recherches de naines brunes, objects substellaires ayant des masses comprises entre les planètes géantes et les naines M de faible masse.

21.1 Introduction

Between the giant planets such as Jupiter (10^{-3} $M_{\odot}$) and stars at the bottom of the hydrogen-burning main sequence ($\leq 0.1M_{\odot}$) – spanning more than two orders of magnitude in mass – the sequence of brown dwarfs has yet to be discovered and analyzed in detail. The previous sentence carries the positive bias of this author that – despite the current lack of a single, unambiguous example for me to discuss at this meeting – the flurry of searches now underway by a variety of techniques will identify at least some genuine brown dwarfs during the present decade. Our motivation for thinking and speaking positively is to encourage advances in the theory of both the interiors and atmospheres of such gaseous objects, in order to make possible positive identifications among the candidates found by observers. Indeed, numerous candidates exist of different kinds, some with measured masses, luminosities and temperatures which straddle the stellar mass limit (SML) near 0.08 $M_\odot$.

This paper is the observational complement to Bill Hubbard's, in which recent theoretical modelling of objects near and below the SML mass limit is discussed. One area of rapid and important theoretical progress not addressed by Dr. Hubbard is the application of new stellar atmosphere analyses to fit the infrared and optical spectra of very low mass stars and, potentially, the more luminous brown dwarfs. I will review this work briefly in Section 2. The remaining sections are devoted to overviews of the different techniques used in current searches, and the recent results. Most of this material is discussed much more extensively in Burrows and Liebert (1993), but there are some updated references and new results.

21.2 Low Mass Stars or Brown Dwarfs?

In the solar neighborhood, the most accurately determinable stellar parameter is often the luminosity. This is because a large, accurate trigonometric parallax combined with measurements of multiple colors yields a good estimate of the bolometric flux even if the temperature is poorly known. To look at the situation in simpler, observational terms: if the magnitude at K(2.2μ) is known, the bolometric correction is small, and the luminosity may be estimated. It might therefore seem appropriate to establish the relationship between mass and luminosity near the bottom of the main sequence, in order to determine whether a given candidate is below the SML. We shall see, however, that this is not possible.

21.2.1 The Mass – Luminosity Relation

On the hydrogen-burning main sequence, the luminosity is of course a monotonic and steeply-increasing function of mass. Note that a low mass star has a hydrogen-burning lifetime that is much longer than the age of the Galaxy. Hence, the so-called "zero age" main sequence (ZAMS) position at a given mass and chemical composition remains unchanged for time scales of interest to us. The mass below which hydrogen-burning cannot continue indefinitely is near 0.075-0.08 $M_\odot$for the solar composition.

The main sequence luminosity is often expressed as a power law of the mass with the exponent varying from approximately three for massive stars to nearly five below the solar mass. Such a relationship is also valid on the low mass main sequence (with smaller slope) until the approach to the stellar mass limit. The predictions of stellar interiors models have been tested empirically by comparing stars with measured masses (and luminosities) – in astrometric binary systems. Henry and McCarthy (1993) have added an impressive number of new binary components using their technique of infrared speckle interferometry. Using the absolute K magnitude (M_K) which, as we pointed out, is closely related to the log of the luminosity, they found a simple power law fit for the mass,

$$log M/M_\odot = -0.166 M_K + 0.560$$

which is an excellent fit to the 0.1-1 $M_\odot$range.

The problem comes in extending the fit below 0.1 $M_\odot$towards the stellar mass limit, where several complications arise. First, the theory predicts that, as the stellar mass limit is approached, the M-L function will steepen radically – that is there will be a much larger decrease in luminosity over a given interval decrease in mass. Second, the pre-main sequence phase prior to the ZAMS lasts longer with decreasing mass, and below 0.1 of solar the objects require over 10^9 years to reach the ZAMS. Thus, the M–L relation becomes a substantial function of the *age* of a star. Moreover, below the SML the (substellar) objects never reach the ZAMS. Again, their phase of gravitational contraction brings them slowly through the same luminosities as the dimmest ZAMS stars. Finally, there are the so-called "transition" objects predicted to have masses of 0.07–0.075 $M_\odot$ for solar composition, which undergo limited hydrogen-burning for up to a few Gyr, though this energy release is unable to halt the contraction and growing degeneracy of the core. Nonetheless, before entering the brown dwarf cooling sequence, they may linger for these relatively long times in the luminosity range of the faintest ZAMS objects. Thus, we must know the age of a stellar object at a given low luminosity, before a mass can be assigned to it from its luminosity.

21.2.2 Temperature Estimates from Spectra and Model Atmosphere Fits

The effective temperature (T_e) estimates for very low mass stars have been very poor up to now and, until recently, based almost entirely on fits of observed colors to blackbodies. Now it is well known that the blackbody shape is a very poor approximation to the energy distributions of these objects. However, there had been relatively little attention to studying the spectra and atmospheres of stars on the M dwarf sequence, the hydrogen-burning main sequence stars of lowest mass. This neglect has been due primarily to the complexity of especially the molecular opacity sources in such cool stars.

In recent years there has been impressive progress on some of the most relevant of the molecular band systems, such as CO, TiO and H_2O. The two PhD dissertations of Allard (1990) at the University of Heidelberg and Ruan (1991) at the Australian National Observatory have changed this bleak situation. These resulted in the first model atmosphere grids reaching down to temperatures appropriate to the SML, and both demonstrated fair success in matching infrared and optical spectra of M dwarfs.

The result of the analysis using the Allard model atmospheres was a set of temperatures for low mass stellar "standards" – well-studied, bright stars in the solar neighborhood. When spectra extending from 0.6 to 1.55 μ were fitted with synthetic spectra from models with solar composition and log $g = 5$, the first real attempt at defining a temperature scale for low mass stars based on model atmospheres (Kirkpatrick et al. 1993). Now these can be combined with the more accurate luminosities to place the objects in the astronomers' favorite diagram, and compare these with the predictions of theory as a function of mass and chemical composition.

21.2.3 The Hertzsprung–Russell Diagram

Fig. 1 is a Hertzsprung–Russell (HR) Diagram, a plot of log $L/L_{\odot}$vs. log T_e, in which the stars from Kirkpatrick et al. (1993) are shown as filled circles. Examples of the blackbody temperature determinations are shown as open circles in the diagram. Also shown for comparison are theoretical interiors calculations for masses approaching the stellar mass limit of 0.08 $M_{\odot}$. It is perhaps not too much of a surprise that the model fits give T_e values closer to the predicted locations than the blackbody fits, except for the coolest stars of lowest luminosities. However, the spectroscopic fits are far from perfect over the wavelength range covered. Moreover, Tinney, Mould and Reid (1993) show that Allard models give a poor fit to the spectral energy distributions observed at longer infrared wavelengths. There is clearly much work to be done in refining the temperature and HR diagram determinations for stars of the lowest masses.

Also shown in Fig. 1, however, are a few tracks showing the very real evolution in this diagram of substellar objects. These brown dwarfs fall towards the main sequence in their phase of gravitational contraction, and limited nuclear burning for those with "transition" masses. Finally, they enter the cooling sequence at a fixed radius with the onset of degeneracy. During these phases the figure shows how closely their evolution parallels the main sequence, although the brown dwarf always reaches a given luminosity in a shorter time. Thus, the ambiguity of the stellar luminosity is not resolved – at least not easily – by using the effective temperature.

It is nearly impossible, therefore, to distinguish a brown dwarf fairly near the SML from a stable star, based on position in the HR Diagram alone. The temperature of the brown dwarf is typically only a few hundred degrees lower than the star at a given luminosity. We have already seen that the T_e assignable to a low mass star is at least that uncertain.

Either of two additional stellar parameters may provide enough information to resolve the ambiguity – that is, determine whether a given low luminosity object is a star or a brown dwarf. These are the *mass* or the *age*. We have already mentioned the growing sample of nearby stars where the masses are estimated from the solutions to the binary orbit. Likewise, in young clusters or associations where the age may be known, single objects may be analyzed.

21.3 Searching for Field Stars

21.3.1 Proper Motion Surveys

Selection by motion on the sky has been the traditional way of finding the Sun's nearest neighbors. The most important survey to date was that of Luyten (1963) using plates taken with the Palomar 1.2-meter Schmidt telescope at two different epochs generally some 12 years apart; the first epoch was the original Palomar Sky Survey of the early 1950s. The sample one assembles has a kinematic bias – for example, the stars which happen to have the smallest tangential velocities with respect to the Sun might be missed. However, this has been a very efficient way of finding solar neighbors over the entire sky. The nearest, low luminosity stars to the Sun are those amenable to the most accurate followup observations – trigonometric parallaxes, searches for companions, etc.

The least luminous of the solar neighbors currently are two stars cataloged in Luyten (1979) as LHS 2924 and 2065, each with absolute visual magnitudes (M_V) fainter than +19, implying luminosities of a few x $10^{-4} L_\odot$. Such luminosities place them very close to the bottom of the ZAMS (Fig. 1), but also in the realm of the young brown dwarfs.

21.3.2 Optical and Infrared Color Surveys

The red colors of the lowest-mass stellar objects provide a method of selection free of kinematical bias. With the availability of sensitive emulsions,

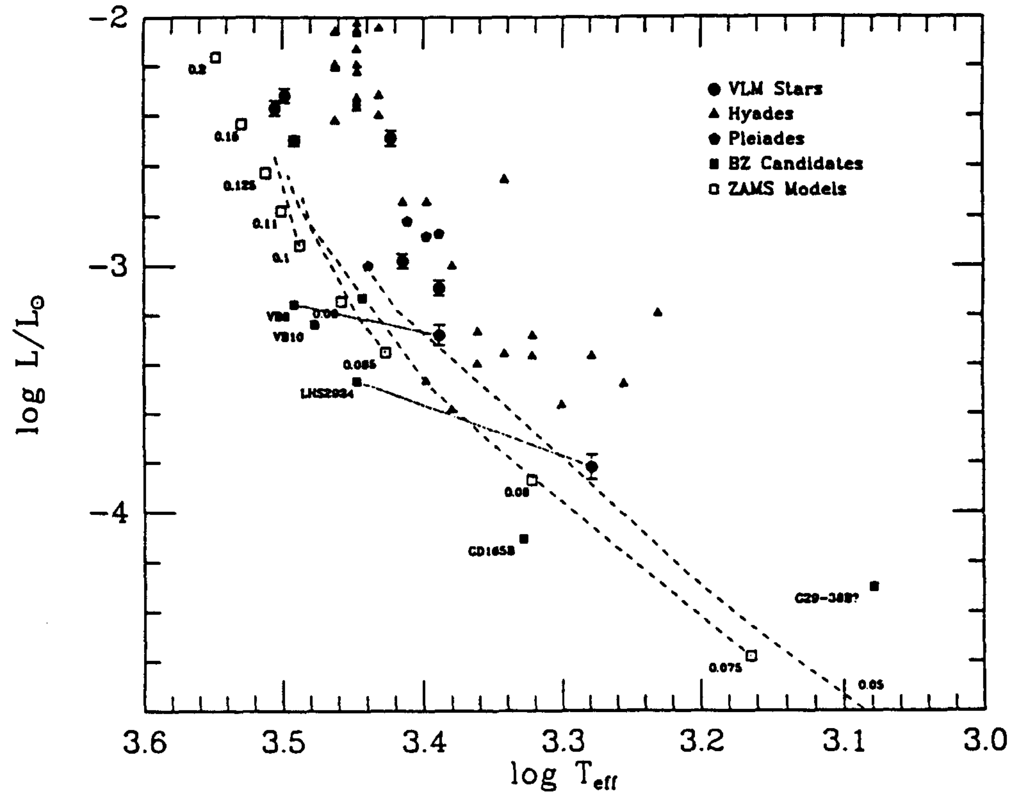

Fig. 21.1 The HR Diagram, showing the near juxtaposition of stellar and substellar masses of differing ages (from Burrows and Liebert 1993, their Fig. 19).

automated measuring machines, and sophisticated computers, large photographic color surveys have been carried out over large areas of the sky at high galactic latitude (where contamination by red giants and heavily-reddened background stars is not a problem). Gilmore and Reid (1983) presented the first large samples, as did Hawkins (1986) and his collaborators. Still, the surface area of the sky covered by the color surveys does not yet approach that of the Luyten proper motion surveys. Hence, using redder colors they must go to larger distances than the Palomar Sky Survey and necessarily find objects that are more difficult to study in detail. In particular, the measurement of trigonometric parallaxes might be more difficult, so that the luminosities of objects which may be below $0.1 M_\odot$ may have to be assigned from photometric colors.

Using the new Palomar Sky Survey of the 1980s, Tinney, Reid and Mould

(1993) have combined both proper motion and color selection into a more comprehensive attempt at finding low mass stars. Their project includes the measurement of trigonometric parallaxes as well. This sample promises to be the best collection of "field" stars. Already they have identified stellar objects somewhat fainter than the LHS stars mentioned previously. Tinney (1993) argues that the faintest known stars may not be stably supported by nuclear burning.

An example of a more specialized color survey is that of Kirkpatrick (1992) using photometric CCD data rather than photographic magnitudes. He presents evidence in agreement with Tinney's (1993) conclusion about the faintest field stars. Finally, we note that one of the coolest known objects of this type – called PC 0025+0447 – was found as part of a survey for high-redshift QSOs (Schneider et al. 1991). This object is characterized by a color somewhat redder than the benchmark LHS stars, as well as extremely strong Hα emission. Unfortunately, its luminosity is not measured, nor is the survey characterized to find a complete sample of very red stellar objects which might lack strong emission.

21.4 Searching in Young Clusters

The advantages of confining the search to members of a young stellar aggregation are obvious. First, the objects will be young and relatively luminous. Secondly, they should have at least approximately the same ages, so that it will be possible to assign masses based on an estimate of the luminosity alone. Furthermore, all candidates lie at the same known distance – that is, if they really are members of the cluster or group. Finally, there are several interesting aggregations close enough for observation – ranging from molecular clouds forming stars of order 10^{6-7} years to clusters nearly as old at 10^9 years. The development of large format CCD and infrared arrays has made observation of accurate colors over large regions of a cluster possible.

The disadvantages are also formidable. Star-forming regions may be in the galactic plane, so that heavily reddened background stars may be confused with genuinely cool members of an association. Newly formed stars may possess a remnant accretion disk and/or strong chromospheric activity, which may distort the spectral energy distribution from that of a simple photosphere. Furthermore, the youngest groups may have a significant spread in age. All of these problems are generally magnified the younger the aggregation is. Finally, the candidates themselves are relatively far away and faint compared to field objects found in the solar neighborhood or in the color surveys, such that the opportunities for followup observations are limited.

21.4.1 Star-Forming, Molecular Clouds

The youngest star-forming regions where it might be worth looking for luminous substellar objects are of the order of 10^6 years old, and range in density from the loose Taurus–Auriga clouds to Rho Ophiuchus, a giant molecular cloud and newly-forming star cluster. Both happen to be approximately 150 pc away. No clear success has been achieved with the former, which is characterized by a treacherous, heavily-reddened stellar background. Rho Ophiuchus differs in having a very high *internal* extinction of $A_V > 50$ magnitudes. The work has been carried out exclusively in the infrared, especially the K band, using wide–format arrays. An exhaustive review of the work on Rho Oph is beyond the scope of this paper, but I will mention a recent highlight.

Comeron, Rieke, Burrows and Rieke (1993) have now completed a survey of 200 square arc minutes to a completeness of $K = 15.5$. They have found 91 faint sources, all with multiple observations in $H(1.6\mu)$ and K. They used the color information to estimate the (highly variable) extinction to each object and hence the luminosity. Then, comparison with a theoretical isochrone for an assumed age of (up to) 2 x 10^6 years yields a unique mass for each luminosity. Perhaps seven objects have indicated masses at or below $0.05 M_\odot$– well below the SML! The method is simple and straightforward, since the amount of information is quite limited. In order to pursue these candidates further, it may be necessary to have a better understanding of the infrared spectra and energy distributions of low mass stellar and substellar objects.

21.4.2 The Pleiades and Hyades

These clusters have attracted the most attention in the search for substellar objects of known age – that is, 6-7 x 10^7 years for the Pleiades and 6 x 10^8 for the Hyades. Since the latter is closer to the Sun (44 vs. 125 pc) it turns out that the predicted apparent brightnesses of their respective brown dwarf sequences would be very similar. We have space here to discuss only a few of the many searches in the fields of these clusters.

Stauffer et al. (1989) surveyed some 900 sq. arcmin at V and I using a CCD detector. They found several good candidates which are likely to be members based on radial velocities and Hα emission line activity (Stauffer et al. 1994). However, the first paper concluded that the mass function peaked near $0.2M_\odot$ and hence it was unlikely that the cluster had a high density of substellar objects. A deeper CCD survey has been published by Simons and Becklin (1992), which can penetrate well into the brown dwarf luminosity regime. At the moment, the implication of this work is not yet clear to this author.

The most comprehensive and complete Pleiades survey is that of Hambly & Jameson (1991) and Hambly, Hawkins and Jameson (1991; HHB), using Schmidt photographic plates at R and I to study a three degree diameter field – the core of the cluster. The second citation above includes proper motion measurements to determine with fairly high probability the stars which are astrometric members of the cluster – of those which have appropriate magnitudes and colors to fit the predicted Pleiades low mass pre-main sequence.

To illustrate how this double-selection method works, we show in Fig. 2 the plot of proper motions measured in the Pleiades field by HHB. The vast majority of background stars form a huge "core" near zero velocity. But an excess of stars clearly appears at the Pleiades velocity (lower southeast circle), which fortunately is well offset from zero. Still, some allowance for a background having this same velocity is necessary, and a "control field" (eastern circle) helped HHB estimate that number. Secondly, they plotted the candidates surviving astrometric selection into an I–R – –I color magnitude diagram (Fig. 3), for both the Pleiades and astrometric control field. The diagonal line is the expected locus of the main sequence at the Pleiades distance. Clearly there is an excess of points in the set with Pleiades motions corresponding to possible pre-main sequence objects above the diagonal line, with very few such points in the control field. Nonetheless, HHB could not expect that 100% of the candidates surviving both tests are actual Pleiades low mass stars and brown dwarfs. Further confirmation can be achieved with radial velocity measurements: Stauffer, Liebert, Giampapa and Hambly (1994, in preparation) indicate that this survey has selected brown dwarf and very low mass stellar members with high efficiency.

The Hyades is sufficiently old that the luminosity function (LF) should have separated into distinct lower main-sequence and brown dwarf components. Due to the size or relative looseness of the cluster – and, ironically, its proximity to the Sun – it is difficult to establish membership reliably from proper-motion measurements alone. Moreover, a new astrometric study (Reid 1992) shows evidence for mass segregation; thus the lower-mass objects may be less centrally concentrated and hence even more difficult to identify as cluster members against a difficult background field.

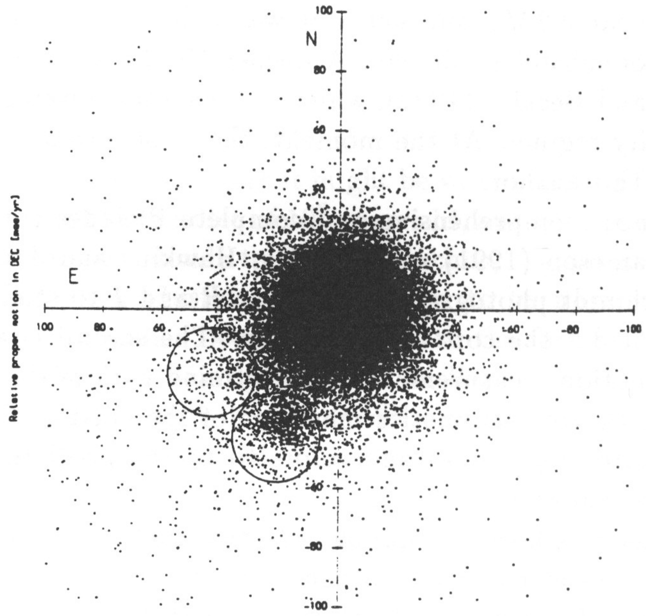

Fig. 21.2 Proper motion diagram from the Pleiades field of Hambly, Hawkins and Jameson (1991, HHB – their Fig. 1), as discussed in the text.

Leggett and Hawkins (1988, 1989) selected field stars with large $R-$ $-I$ colors for followup infrared (JHK) photometry and derived infrared LFs. Again, there was evidence of a peak in the LF near $M_K \sim +6.7$ (or $\sim 0.2M_\odot$). Bryja et al. (1992) identified several faint, red objects on multiple epochs of red Palomar Sky Survey plates as brown dwarf candidate members. The visual–infrared color measurements were somewhat puzzling, though spectroscopic followup work has strengthened the case for at least a few of these stars. This work is still in progress, as is an I and K band imaging project by Macintosh et al. (1992).

21.5 Discovery and Analysis of Substellar Companions

For stellar objects in close binary systems, the masses may be determined directly by analysis of the binary orbits. The observational techniques include direct photography of visual binaries near the Sun, astrometric perturbation analyses, and speckle interferometry especially at infrared wavelengths. But wider pairs are even easier to find and at least the luminosity of a faint companion can be established.

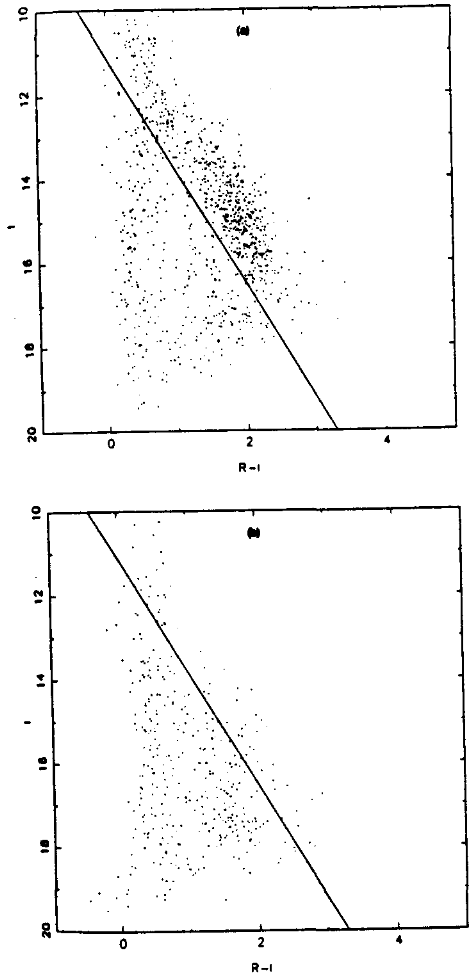

Fig. 21.3 The color magnitude diagram for the Pleiades candidates surviving astrometric selection (top) and from a control field, as discussed in the text. (from HHB)

21.5.1 Wide Optical Companions

Photography of the fields around nearby stars has been employed for decades to discover resolved companions sharing the space motion of the primary. Several early "benchmark" stars of low luminosity were found by van Biesbroeck (1961); vB8 and vB10 are among the best studied of these. The latter, at $M_V \sim +18.7$, was the least luminous known star until the 1980s.

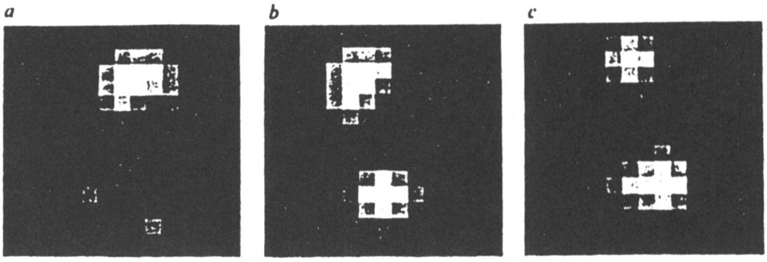

Fig. 21.4 Infrared images of the 10,000 K white dwarf GD 165 (top) in $J(1.2\mu)$, $H(1.6\mu)$, and $K(2.2\mu)$ from left to right, taken from Becklin and Zuckerman (1988).

21.5.2 Infrared Imaging and Photometry

Continuation of the search for fainter, resolved companions in recent years has employed new infrared array detectors to search at friendlier wavelengths. Skrutskie, Forrest and Shure (1989) found only one new very low luminosity companion in their survey of known, nearby stars, and this Gliese 569 (Forrest, Skrutskie, and Shure 1988) is luminous enough to be a main sequence star. An even deeper survey to $K = 15.5$ of all northern stars to distances out to 8 pc (G.H and M.J. Rieke, 1992 private communication) found no plausible brown dwarf candidates.

The most exciting discoveries by this method are infrared detections around white dwarf stars, by E.E. Becklin and B. Zuckerman. The white dwarf GD 165 has a companion at least 120 a.u. away, with a color temperature of 2100 K and luminosity of 8 x $10^{-5} L_{\odot}$(Becklin and Zuckerman 1988), substantially cooler and fainter than any well-studied field star. The infrared images (Fig. 4) show a companion star dramatically cooler than its white dwarf primary at a separation of 4.3 arcsec. The companion is not detected at 1.2μ (left frame), but is brighter than the primary at 2.2μ (right). GD 165B also exhibits a very late type spectrum (Kirkpatrick, Henry and Liebert 1993). Nonetheless, various authors have shown that GD 165B may fit tracks of marginally stellar mass.

A more puzzling but potentially more decisive case is the unresolved infrared excess of the white dwarf G 29–38 (Zuckerman and Becklin 1988). If due to a brown dwarf companion, as these authors originally suggested, the separation on the plane of the sky cannot exceed several a.u. However, detections of flux longward of 2μ out to 10μ led Telesco, Joy and Sisk (1990)

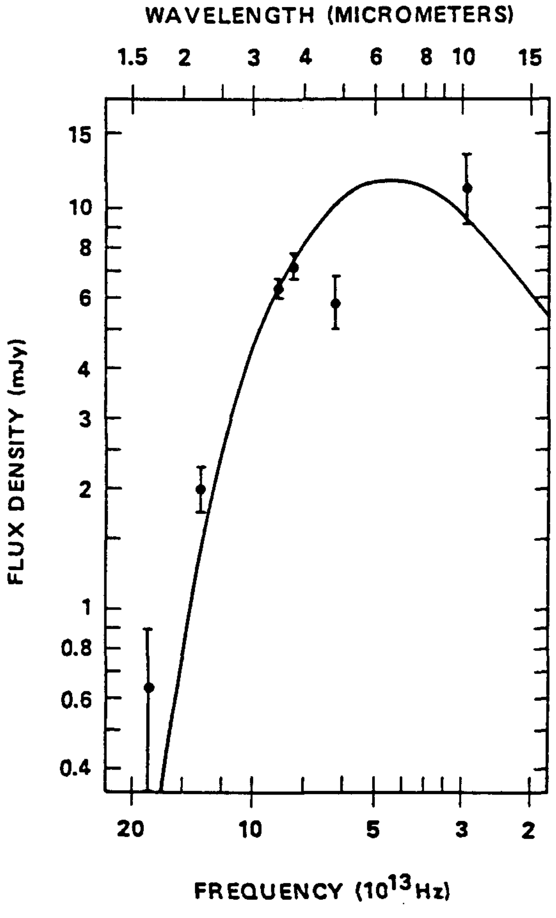

Fig. 21.5 Unresolved excess far-infrared emission from G 29-38, with an 800 K blackbody fit. Shortward of 2μ the flux of the white dwarf primary star dominates. (from Tokunaga, Becklin and Zuckerman 1990).

and Tokunaga, Becklin and Zuckerman (1990) to attribute the infrared flux to some kind of cooler dust shell around the white dwarf. The far-infrared energy distribution presented in the latter reference is shown in Fig. 5. The fit suggests that the dust has a temperature near 800 K.

It was logical to ask how a white dwarf with a cooling age of 10^9 years could retain such a warm dust shell? However, the age of the white dwarf poses a problem for a brown dwarf interpretation as well, since, if the infrared luminosity were attributed primarily to a companion, it could not be very old. Finally, Barnbaum and Zuckerman (1992) report that G 29-38 is probably a small amplitude (5-10 km s^{-1}) radial velocity variable with a possible period near 11 months; this could be consistent with a substellar mass companion less than an a.u. away. The study of this fascinating object must continue.

21.5.3 Infrared Speckle Interferometry

Henry and McCarthy (1990, 1992) have used two-dimensional speckle interferometric observations to survey a complete sample of nearby stars out to 8 pc for faint companions most easily detectable at 2.2 μ. Multiple observations of the separation and position angle of newly-discovered and previously-known binary systems lead to improved determinations of the masses (and luminosities) of low mass stars and brown dwarf candidates. These serve as the data points for their mass–luminosity function discussed earlier.

The Henry and McCarthy (1992) LF declines sharply at $M_K \sim +10$. In most cases, if companions two magnitudes fainter existed, they would have been found over a wide range of separations. The Zuckerman and Becklin (1992) search for companions to white dwarfs produced a very similar LF – and sharp decline at the faint end – despite the discovery of GD 165B.

21.5.4 Radial Velocity Surveys

A complementary technique to the various imaging approaches for finding unresolved companions to nearby stars is to search for radial velocity variations due to the orbital motion of a visible component. The stars must be bright enough for precise, high-resolution line profiles to be measured.

The most comprehensive search to date (Marcy and Benitz 1989) covered 70 low mass M dwarfs, some 80% of allo known single stars later than dM2 and brighter than $V = 10.5$ accessible from the Northern Hemisphere. Since the brightness constraint requires the stars also to be within 10 pc, there is considerable overlap with the speckle sample, but greater sensitivity to smaller orbital separation. There is also the advantage that the companion need not emit *any* radiation – it need not be a young brown dwarf. As we shall see shortly, however, the inability to study directly the companion is also a disadvantage. Marcy and Benitz (1989) uncovered only one companion that is possibly substellar – Gliese 623B (Marcy and Moore 1988) – which was discovered independently in the infrared speckle work. Again, this star has a possible mass range (0.067–0.087 $M_\odot$) that straddles the SML cutoff.

Several ongoing studies are sensitive to even smaller velocity variations. Campbell, Walker and Yang (1988) and McMillan (1992, private communication) have relative accuracy near 10 *meters* per second. The latter continues a multi-year monitoring of 16 bright solar–type stars.

The most exciting discovery to date from this method happened somewhat circumstantially. Repeated observations of the G dwarf HD 114762 by Latham et al. (1989) were intended to establish this star as a radial velocity standard under an International Astronomical Union program. Instead, they found that the star is variable with a period of 84 days and an amplitude of 0.55 km s^{-1}. The unseen companion has a mass of eleven Jupiters – divided by the sine of the unknown orbital inclination. Thus, if it were viewed less than 8 degrees from pole-on, the companion could still be stellar. A new analysis by Cochran, Hatzes and Hancock (1991) finds an upper limit of only 1 km s^{-1} for the projected rotation rate – suggesting indeed that a pole-on orientation is possible. Now the Harvard–Smithsonian group are engaged in a systematic monitoring program, with a target list including 24 nearby M dwarfs (Mazeh et al. 1990).

21.6 Halo stars, brown dwarfs and *MACHOS*

The stellar mass limit for a halo star of 1/100 solar metallicity is close to $0.1M_{\odot}$(D'Antona 1987); from stellar interiors calculations, we would expect such a boundary star to be substantially more luminous and hotter than its counterpart at solar metallicity. Indeed, a Pop II main sequence is observed to "cut off" near $M_V \sim +14$, as expected, some five magnitudes brighter than the end of the disk sequence (Monet et al. 1992). The Population II main sequence is up to three magnitudes subluminous in comparison to disk stars of the same color (but much higher mass) – hence the low mass halo stars are called M*subdwarfs*. Any existing halo brown dwarfs must be far too low in luminosity to be detectable.

Information on the halo LF and mass function at the faint end is sketchy. Several globular clusters have been observed down to near the mass limit using CCD detectors (Richer et al. 1991), without evidence of a flattening or turnover. However, this ground-based work has necessarily focussed on stars in outer regions of the cluster. Yet there is evidence that the dynamical relaxation would cause the lower mass objects to be less centrally concentrated than more massive stars, so that the mass function would be biased to a steeper slope in such studies. A repaired *Hubble Space Telescope* could perform an unbiased determination of the average cluster mass function.

Likewise, Richer and Fahlman (1992) have now attempted a corresponding mass function for the field halo population from one large–format CCD field. There are formidable problems with this kind of study: even if the stellar needles can be successfully separated from the extragalactic haystack, it is difficult to estimate their space density because the metallicities and distances are poorly determined. The conclusion of these authors that the halo has a steeply–rising halo mass function accounting for the "missing mass" must be regarded with caution, especially since it appears to conflict with other studies. For example, there was no evidence for such cool stars in the comparable study of Tyson (1988, and private communication). Moreover, proper motion studies should have found very efficiently most representatives of this population in the immediate solar neighborhood, yet the ratio of low mass M stars of Pop II to Pop I does not appear to differ from that for more massive stars (Hartwick et al. 1984; C.C. Dahn and Liebert, unpublished).

Nonetheless, the halo mass and luminosity functions remain poorly determined. I suppose that there is also the possibility that virtually all the unseen halo mass is *below* the SML. To account for all of our galaxy's alleged massive halo, however, requires a density of something like 0.5 brown dwarf per cubic parsec!

It is worth asking if there are any other ways of detecting invisible or very faint stellar objects? The proposal of Paczynski (1986) to observe gravitational lensing events of more distant stars by compact, unseen objects in the foreground of our Galaxy generated much excitement as a possible answer to this question. The search for what are commonly called MACHOS – massive, compact, halo objects, a term coined by Kim Griest – has been undertaken by several groups. Since the St. Malo meeting, two groups have reported the first, probable microlensing events of background Large Magellanic Cloud giants by halo objects – the EROS group (Aubourg et al. 1993) and the Livermore group (Alcock et al. 1993). A Polish project tied more directly to Paczynski has also reported a similar detection from the Galactic bulge (Udalski, A. et al. 1993).

What are these microlenses likely to be? It is too early to draw conclusions. A perfectly satisfactory explanation at the moment for the joint EROS–Livermore event with an estimated mass in the 0.03–0.3 $M_\odot$ range, of course, is that this is a low mass star. Time will tell how many such events are found in the well–defined search programs.

21.7 The Bottom Line

What is the net result of the application of all of these attempts to find brown dwarfs in the galactic field populations, in young stellar associations, and as companions to nearby stars? First, it has to be said that not a single.

unambiguous case of a brown dwarf can be pointed to with confidence. Yet, the pessimists must also acknowledge that literally dozens of interesting candidates have been found with this variety of search techniques, and more are being added by the month. The lack of proven examples may be blamed on the great difficulty of establishing a substellar mass. There is a need to sharpen our theoretical tools – through more accurate equations of state and opacities – so that the candidates may be unveiled for what they are. Better theoretical atmosphere, envelope and interior models are needed in order to tell the difference between a brown dwarf and a very low mass star.

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