Abstract.

With the discovery of the companions of 51 Peg, 55 Cnc, τ Boo, υ And, 70 Vir, 47 UMa, and Gl229, evolutionary and spectral models of gas giants and/or brown dwarfs with masses from 0.3 through 60 times that of Jupiter assume a new and central role in the emerging field of extrasolar planetary studies. In this contribution, we describe the structural, spectral, and evolutionary characteristics of such exotic objects, as determined by our recent theoretical calculations. These calculations can be used to establish direct search strategies via SIRTF, ISO, and HST (NICMOS), and via various ground–based adaptive optics and interferometric platforms planned for the near future.

1. Introduction

During the past year, scientists and the public at large have been galvanized by the discovery of planets and brown dwarfs around nearby stars (Mayor & Queloz 1995; Marcy & Butler 1996; Oppenheimer et al. 1995; Butler & Marcy 1996) and
by evidence for ancient life on Mars (McKay et al. 1996). These extraordinary findings have dramatically heightened interest in the age-old questions of where we came from and whether we are unique in the cosmos.

Not unexpectedly, a general understanding of stellar and planetary origins does not yet exist. Planetary science has focussed over the past three decades on the planets of our own solar system and on the chemical and physical clues to their formation accessible by direct examination and sampling. Astronomy has pushed simultaneously outward to cosmology and inward to understand the formation of stars and planets. A long-term goal of theorists should be the integration of these two realms and the creation of a new interdisciplinary science of planets, stars, and life.

The new planet and brown dwarf discoveries (Table 1 and Figure 1) collectively have an exceptional and unexpected range of masses, semi-major axes, eccentricities, and primaries. The unpredicted variety among these new giant planets/brown dwarfs poses fundamental questions about the origin of planetary and stellar systems. While the new planets were all discovered by indirect means, it is only via direct detection (imaging and spectroscopy) that extrasolar planets can be adequately characterized and studied. With this in mind, we have embarked upon a new and thorough theoretical study of the structure, spectra, colors, and evolution of extrasolar giant planets and brown dwarfs (Marley et al. 1996; Burrows et al. 1997).

Table 1. The Bestiary of Brown Dwarfs and Extrasolar Giant Planets

| Object   | Star     | M_\star (M_\odot) | L_\star (L_\odot) | d (pc) | M (M_J) | a (AU) | P (days) | e     |
|----------|----------|-------------------|-------------------|-------|---------|--------|---------|-------|
| HD283750 | K2V?     | 0.75?             | 0.27              | 16.5  | >50     | ~0.04  | 1.79    | 0.02  |
| τ Boo B  | F7V      | 1.25              | 2.5               | 15    | >3.87   | 0.046  | 3.313   | 0.018 |
| 51 Peg B | G2.5V    | 1.0               | 1.0               | 15.4  | >0.47   | 0.05   | 4.23    | 0.0   |
| HD98230  | G0V      | 1.1               | 1.5               | 7.3   | >37     | 0.05   | 3.98    | 0.0   |
| ν And B  | F7V      | 1.25              | 2.5               | 17.6  | >0.68   | 0.058  | 4.61    | 0.19  |
| 55 Cnc B | G8V      | 0.85              | 0.5               | 13.4  | >0.84   | 0.11   | 14.65   | 0.051 |
| HD112758 | K0V      | 0.8               | 0.4               | 16.5  | >35     | <0.35  | 103.22  | 0.16  |
| HD114762 | F9V      | 1.15              | 1.8               | 28    | >10     | 0.38   | 84      | 0.25  |
| 70 Vir B | G4V      | 0.95              | 0.8               | 18.1  | >6.6    | 0.45   | 116.6   | 0.40  |
| HD140913 | G0V      | 1.1               | 1.5               | ?     | >46     | ~0.54  | 147.94  | 0.61  |
| HD89707  | G1V      | 1.1               | 1.3               | 24.5  | >54     | 0.69   | 198.25  | 0.95  |
| BD -04782 | K5V     | 0.7               | 0.1               | ?     | >21     | ~0.7   | 240.92  | 0.28  |
| HD110833 | K3V      | 0.75              | 0.2               | 16    | >17     | ~0.8   | 270.04  | 0.69  |
| HD217580 | K4V      | 0.7               | 0.1               | 18.5  | >60     | ~1.0   | 1.24    | 0.52  |
| HD18445  | K2V      | 0.75              | 0.2               | ~20   | >39     | 1.2    | 1.52    | 0.54  |
| 16 Cyg B | G2.5V    | 1.0               | 1.0               | 22    | >1.5    | 1.7    | 2.19    | 0.67  |
| 47 UMa B | G0V      | 1.1               | 1.5               | 14.1  | >2.4    | 2.1    | 2.98    | 0.03  |
| HD29587  | G2V      | 1.0               | 1.0               | 42    | >40     | 2.1    | 3.17    | 0.0   |
| Gl 411 B | M2V      | 0.4               | 0.02              | 2.52  | >0.9    | 2.38   | 5.8 y    |     |
| 55 Cnc C | G8V      | 0.85              | 0.5               | 13.4  | >5      | 3.8    | >8 y    |     |
| Jupiter  | G2V      | 1.0               | 1.0               | 0.0   | 1.00    | 5.2    | 11.86   | 0.048 |
| Saturn   | G2V      | 1.0               | 1.0               | 0.0   | 0.3     | 9.54   | 29.46   | 0.056 |
| Gl 229 B | M1V      | 0.45              | 0.03              | 5.7   | 30-55   | 44.0   | >400    |     |

However, building upon our previous experience in the modeling of brown dwarfs and M stars, we (Burrows et al. 1995; Saumon et al. 1996; and Guillot
Figure 1. Plots of the effective temperature ($T_{\text{eff}}$) versus mass (in units of $M_J$) (top panel) and of radius (in units of $R_J$) versus mass (bottom panel) for some of the newly-discovered planets and/or brown dwarfs. The effective temperature and radius ranges reflect the ambiguities in the Bond albedo, and the mass ranges reflect a factor of two spread in sin(i) (except for Gl229 B). The dotted curves are 10$^{10}$-year isochrones that nicely bound the family. Stellar insolation effects have been included. Lalande 21185 is depicted by a small vertical line in both panels. To the right in the top panel the lines depict the range of $T_{\text{eff}}$’s for which the indicated species condense out near the photosphere. Hence, H$_2$O vapor features should be absent from the spectra of 70 Vir b and 47 UMa b, since H$_2$O in those objects might be in the form of clouds. In addition, Mg$_2$SiO$_4$ and Fe clouds might be in evidence in the spectra of $\tau$ Boo b, v And b, and 51 Peg b, if they are indeed gas giants.
et al. 1996) first published grey models of extrasolar giant planets (EGPs). This early generation of EGP models in the mass range 0.0003 \( M_\odot \) to 0.015 \( M_\odot \) (\( \sim 0.3 \, M_J \) to \( 15 \, M_J \)) was in aid of both NASA’s and ESA’s (Leger 1993) embryonic plans to search for extrasolar planets. Figure 2 depicts the bolometric luminosity evolution of EGPs for ages from \( 10^6 \) to \( 5 \times 10^9 \) years. Note that younger and more massive objects are significantly brighter and, hence, more easily detected.

Some of the space platforms and new ground–based facilities that have or will obtain relevant infrared and optical data include the HST (WFPC2, NICMOS), the IRTF, the MMT 6.5-meter upgrade, the Large Binocular Telescope (LBT) (planned for Mt. Graham), Keck’s I and II (with HIRES), the European ISO, UKIRT, and SIRTF, along with a large number of medium– to large–size telescopes optimized or employed in the near–infrared. One project of Keck I and II, under the aegis of NASA’s ASES–0 (Astronomical Study of Extrasolar Planetary Systems) program, will be to search for giant planets around nearby stars. A major motivation for the Palomar Testbed Interferometer (PTI) supported by NASA is the search for extrasolar planets. Recently, Dan Goldin, the NASA administrator, outlined a program to detect planetary systems around nearby stars that may become a future focus of NASA. This vision is laid out in the Exploration of Neighboring Planetary Systems (ExNPS) Roadmap (see also the “TOPS” Report, 1992).

2. Early Calculations of the Evolution and Structure of Extrasolar Giant Planets

Earlier work generally consisted of evolutionary models of planets of 1 \( M_J \) and below, beginning with Graboske et al. (1975). That work explored the evolution of the low–mass objects Jupiter and Saturn from an age of \( 10^7 \) years to the present (\( \sim 4.6 \) Gyr). Working down from higher masses, Grossman and Graboske (1973) extended their calculations of brown dwarf evolution to as low as 12 \( M_J \), but had to limit their study to ages less than about 0.1 Gyr. Black (1980) used the results of Grossman & Graboske (1973) and Graboske et al. (1975) to infer simple power-law relations for the variation of luminosity \( L \) and radius \( R \) as a function of mass \( M_p \) and time \( t \). Black’s relations are roughly valid for objects close in mass to 1 \( M_J \) and close in age to 4.5 Gyr. However, Black’s formulas become inaccurate at earlier ages and at larger masses.

EGPs will radiate in the optical by reflection and in the infrared by the thermal emission of both absorbed stellar light and the planet’s own internal energy. In Burrows et al. (1995), Saumon et al. (1996), and Guillot et al. (1996), we evolved EGPs with masses \( (M_p) \) from 0.3 \( M_J \) (the mass of Saturn) through 15 \( M_J \) and included the effects of “insolation” by a central star. Giant planets may form preferentially near 5 A.U. (Boss 1995), but as the new data dramatically affirm, a broad range of \( a \) s can not be excluded. Whether a 15 \( M_J \) object is a planet or a brown dwarf is largely a semantic issue, though one might distinguish gas giants and brown dwarfs by their mode of formation (e.g. in a disk or

1We use this shorthand for Extrasolar Giant Planet, but the terms “exoplanet” or “super–jupiter” are equally good.
Figure 2. Bolometric luminosity ($L_{\text{bol}}$) in solar units of a suite of EGPs placed at a distance of 5.2 A.U. from a G2 V star versus time ($t$) in Gyr. The reflected luminosity is not included, but the absorbed component is. At $t \sim 0.2$ Gyr, the luminosity of the 14 M$_J$ EGP exceeds that of the 15 M$_J$ EGP because of late deuterium ignition. The data point at 4.55 Gyr shows the observed luminosity of Jupiter. The 0.3 M$_J$ EGP exhibits a strong effect of warming by the G2 V primary star at late stages in its evolution. Although this model resembles Saturn in mass, here it is placed at the distance of Jupiter from its primary. (The flattening in $L$ vs. $t$ for low masses and great ages is a consequence of stellar insolation.) The insert shows, on an expanded scale, the comparison of our lowest-mass evolutionary trajectories with the present Jupiter luminosity (from Burrows et al. 1995).
Physically, compact hydrogen-rich objects with masses from 0.00025 $M_\odot$ through 0.25 $M_\odot$ form a continuum. However, EGPs above $\sim 13 M_J$ do burn deuterium for up to $10^8$ years.

3. New Evolutionary and Spectral Models of EGPs

On the same October day on which 51 Peg B was reported (Mayor & Queloz 1995), a Caltech team announced the direct detection of the brown dwarf Gliese 229 B (Geballe et al. 1995; Oppenheimer et al. 1995; Nakajima et al. 1995; Matthews et al. 1996). Using a prototype adaptive optics system on the old MMT, Roger Angel of Steward Observatory obtained a K–band image of Gl 229 B, thus confirming its detection. This object has an estimated luminosity of $6.4 \pm 0.6 \times 10^{-9} L_\odot$, an effective temperature below 1200 K, and clear signatures of methane and H$_2$O vapor in its spectrum. Since there can be no stars cooler than 1700 K, with luminosities below $5 \times 10^{-5} L_\odot$, or with methane bands, Gl 229 B’s status as one of the long–sought brown dwarfs is now unimpeachable.

To constrain the properties of the brown dwarf Gl229 B, we (Marley et al. 1996) constructed a grid of non–grey model atmospheres with $T_{\text{eff}}$ ranging from 700 to 1200 K and $10^4 < g < 3 \times 10^5$ cm s$^{-2}$. We assumed a standard solar composition for the bulk of the atmosphere. Refractory elements (for example Fe, Ti, and silicates) condense deep in the atmosphere for $T_{\text{eff}} \approx 1000$ K, and thus have negligible gas–phase abundance near the photosphere, as is also true in the atmosphere of Jupiter. For an atmosphere similar to that of Gl229 B, chemical equilibrium calculations indicate that C, N, O, S, and P are found mainly in the form of methane (CH$_4$), ammonia (NH$_3$), water (H$_2$O), hydrogen sulfide (H$_2$S), and phosphine (PH$_3$), respectively.

Our model atmospheres incorporate opacities due to collision–induced absorption by H$_2$-H$_2$ (Borysow & Frommhold 1990) and H$_2$-He (Zheng & Borysow 1995, and references therein), free-free absorption by H$_2$ (Bell 1980), bound-free absorption by H$^-$ (John 1988), and Rayleigh scattering. The absorptions of NH$_3$, CH$_4$, and PH$_3$ are calculated using the HITRAN data base (Hilico et al. 1992) with corrections and extensions. Additional tabulations are used where necessary for CH$_4$ (Strong et al. 1993), especially shortwards of 1.6 $\mu$m. Data for H$_2$O and H$_2$S are computed from a direct numerical diagonalization (Wattson & Rothman 1992; Schwenke et al. 1997). Absorption by CO (Pollack et al. 1993) and PH$_3$ opacity is included in the spectral models, but not in the temperature profile computation. The baseline models assume that the atmosphere is free of clouds. This assumption must be reconsidered in the future (see Figure 1).

For the temperature profile computation, molecular opacity is treated using the k–coefficient method (Goody et al. 1989). After a radiative–equilibrium temperature profile is found, the atmosphere is iteratively adjusted to self-consistently solve for the size of the convection zones, given the specified internal heat flux. With the radiative–convective temperature–pressure profiles, high-resolution synthetic spectra can be generated by solving the radiative transfer equation.

Figure 3 shows a comparison of a theoretical spectrum of Gl229 B with the UKIRT spectrum from 1 to 2.5 $\mu$m s. Including stray light in the optics improves the fit in the H$_2$O troughs dramatically and a $T_{\text{eff}}$ near 1000 K is indicated. This
Figure 3. A comparison of the observed UKIRT spectrum of Gl229 B with a recent theoretical spectrum, including the effects of stray light in the optics. The scattered light fills in the troughs that theory says would otherwise be very much deeper. The discrepancy at the shorter wavelengths may be a consequence of Rayleigh scattering by “clouds” in the atmosphere of Gl229 B and is not due to the presence of TiO or metal hydride absorbers present in M dwarf atmospheres.

As part of our recent theoretical explorations after the Gl229 B campaign, we have found significant flux enhancements relative to blackbody values in the window at 4–5 µm and in the J (1.2 µm) and H (1.6 µm) bands for $T_{\text{eff}}$s from 100 through 1300 K. At temperatures below ~600 K, the widely-used K band at 2.2 µm is greatly suppressed relative to the J and H bands by strong CH$_4$ and H$_2$–H$_2$ absorption features. The J, H, and M band enhancements are a consequence of the opacity holes in those bands and the significant redistribution of flux caused predominantly by pressure–induced H$_2$ absorption longward of 5 µms and strong absorption features of CH$_4$ and H$_2$O in the near and mid–infrared. Figure 4 depicts some preliminary theoretical spectra for objects from 99 to 880 K at a gravity of $3 \times 10^4$ cm s$^{-2}$ (Burrows et al. 1997). Infrared colors derived from these spectra are easily distinguished from those of M dwarfs. In particular, J-K and H-K colors get bluer with decreasing $T_{\text{eff}}$ and are shifted
Figure 4. A comparison with the corresponding blackbody spectra of some preliminary theoretical spectra from 99 to 880 Kelvin for EGPs and brown dwarfs at $3 \times 10^4$ cm s$^{-2}$, in isolation. Plotted is $\nu F_\nu$ versus $\lambda$ in microns, where $F_\nu$ is the flux from the object’s surface, not the flux in a detector. The latter is easily derived knowing the radius as a function of $T_{\text{eff}}$ and gravity. Sufficient flux is redistributed from the longer wavelengths to the near infrared to force a dramatic reappraisal of search strategies. The J, H and M bands are significantly enhanced over the mid–infrared and the K band, though the K band is near the blackbody value for $T_{\text{eff}}$ below $\sim$500 K (from Burrows et al. 1997).
relative to those for M dwarfs and hot brown dwarfs by many magnitudes. The gravity dependence of the emergent spectra is weak. For comparison, in Figure 4 the corresponding blackbody spectra are provided. While the giant planets of the solar system can be helpful guides at the low-$T_{\text{eff}}$ limit of our calculations, the range demonstrated by their spectra warns us against simple generalizations. The extremely non–blackbody nature of both brown dwarfs and extrasolar giant planets is manifest and rather startling. Search strategies should be redesigned accordingly.

4. The Future

The present pace of giant planet discovery and NASA’s future plans for planet searches suggest that many more objects in the Jovian mass range (and above) will be identified and subject to spectroscopic examination. Spectra and colors are worth little if they can not be attached to masses, ages, and compositions. We have already preformed the first rudimentary calculations of the atmospheres, evolution, and spectra of extrasolar giant planets, in a variety of stellar environments. As our recent work on Gl229 B and Figure 4 show, the blackbody assumption can be orders-of-magnitude off in the J, H, L’, and M bands. Therefore, a complete and self-consistent theory of the evolution, colors, spectra, and structure of extrasolar giant planets is a crucial prerequisite for any credible direct search for planets around nearby stars. The new science of extrasolar planets, a merger of both planetary and stellar astronomy, is rapidly being born.

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