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THE EMERGING THEORY OF BROWN DWARFS AND GIANT PLANETS

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The Emerging Theory of Brown Dwarfs and Giant Planets

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Abstract

I summarize some theoretical insights gained in the past two years concerning the spectra, colors, and compositions of brown dwarfs and extrasolar giant planets with effective temperatures below 1300 K. Occupying as they do unique positions in the HR diagram and straddling the realms of the historical planets and the stars, such substellar objects represent an emerging scientific frontier and a means by which the perspectives of Planetary Science and Astronomy can profitably be combined. The recent discoveries of such objects around nearby stars has lent renewed urgency to this endeavor.

I. INTRODUCTION

Stellar astronomy has been a mature science since Astronomy achieved its majority in this century. Stars with respectable masses near or above that of the Sun emit brightly enough in the optical to allow themsleves to be spectroscopically analyzed and characterized. The resulting HR diagrams, spectral sequences, and temperature scales comprise a large fraction of what the modern astronomer learns and uses. However, the region just above and below the bottom edge of the hydrogen main sequence is populated by objects that emit little in the optical, and not much more in the infrared. As a consequence, their study had been retarded by a dearth of data, as well as by woefully incomplete samples. This is starting to change with the identification of a multitude of transition objects in young clusters such as the Pleiades [1], ρ Ophiuchus [2], and Praesepe [3], the watershed discovery of Gl229B [4–7], discoveries in the field (DENIS & 2MASS), and the startling discoveries [8–13] via Doppler spectroscopy of brown dwarfs/giant planets around nearby stars (*e.g.*, τ Boo, 51 Peg, υ And, 55 Cnc, ρ CrB, 70 Vir, 16 Cyg, and 47 UMa).

The hydrogen–rich objects found in this hitherto unexplored realm, be they giant planets, brown dwarfs, or M dwarfs, span three orders of magnitude in mass ($0.00025M_\odot < M < 0.25M_\odot$), a range that exceeds that occupied by garden–variety stars. However, to date their spectra, colors, and evolution have not been subjected to the same degree of theoretical scrutiny. We know all too little about their atmospheres, compositions, and systematics, and, as a result, theory is only marginally prepared to explain and inform the discoveries that new technology will no doubt bring. Nevertheless, theorists

have not been idle and in this paper I will touch on some of the interesting issues, theoretical discoveries, and conundra that are attending the birth of this new discipline. This paper is meant to be a review and a précis; for a more detailed discussion the reader is referred to [14–19].

II. BROWN DWARF AND EXTRASOLAR GIANT PLANET EXOTICA

By definition, brown dwarfs do not burn hydrogen stably on the main sequence, but they can have thermonuclear phases. Objects more massive than $0.07M_\odot$, but less massive than the $\sim 0.075M_\odot$ that marks the solar–metallicity stellar edge, can derive many tens of percent of their luminosity from the truncated $p-p$ chain before they sputter out and cool to blackness. Objects more massive than $0.013M_\odot$ can consume their stores of "primordial" deuterium. During this phase, which lasts from 10^6 to 10^8 years, the object's luminosity can be $\sim$3 times larger than it would have been had its cooling not been partially stabilized by the thermonuclear source. Stars more massive than $\sim 0.06M_\odot$ burn their stock of lithium, leading to the lithium test now being profitably employed to identify "massive" brown dwarfs [26].

Brown dwarf and extrasolar giant planet (EGP) cores contain liquid metallic hydrogen/helium mixtures, have densities from ~ 1 to 2000 gm cm^{-3}, and temperatures that can approach 2.7×10^6 K ($T_{peak} \sim 2\times10^6 M^{4/3}$ K). Surface gravities for the family range from 2×10^3 to 3×10^5 cm s^{-2} and their radii hover around $0.1R_\odot$. After a Hubble time, their luminosities can range from 10^{-5} to 10^{-10} $L_\odot$ and their effective temperatures are below $\sim$ 1700 K. Even without central energy sources, these objects are convective throughout, save for the thin ($\sim 10^{-5}$ by mass) radiative atmospheres that serve as valves to space. At low temperatures and high gravities, their atmospheres are comprised predominantly of molecules such as H_2, H_2O, CH_4, CO, N_2, and NH_3, though many other molecular species should survive in trace amounts. Hazes, clouds, and grains are a major aspect of the brown dwarf/giant planet character, with silicate grains forming for objects with T_{eff}s below $\sim$2500 K, water clouds forming for T_{eff}s below $\sim$ 400 K, and ammonia clouds forming for T_{eff}s below $\sim$ 200 K.

All of the above depend senstitively upon metallicity. In particular, the edge mass and luminosity vary from $0.074M_\odot$ and $6\times10^{-5}L_\odot$ at solar metallicity to $0.092M_\odot$ and $1.3\times10^{-3}L_\odot$ at zero metallicity. However, the radii of substellar objects are only weakly dependent upon metallicity and mass, varying by only $\sim$ 50% at later times and shrinking to below $0.2R_\odot$ within 10^6 years. The peak radius of an old giant planet occurs near 4 jupiter masses. At the densities achieved in such substellar objects, the Coulomb interaction is still quite important in the EOS, but the objects are mostly electron–degenerate and can be viewed as inhabiting a low–mass, hydrogen–rich extension of the white dwarf family. Recently, the radii and masses of the eclipsing late M dwarf pair, CMDra, were measured to a part in 10^2 [27]. These data can be used to check the equations of state employed in M Dwarf/Brown dwarf

modeling, as well as their emissions. While the theoretical radius–mass relation is found to accord well with the observations, there are discrepancies in the luminosities and T_{eff}s for the measured masses of $0.2136 \pm 0.0010 M_{\odot}$ and $0.2307 \pm 0.0010 M_{\odot}$ [27] which can be resolved only when M dwarf atmospheres are better understood.

III. GL229B

The discovery of Gl229B was as a tonic to a subject bedeviled by candidates previously marginalized as merely such. Gl229B contains CH_4 in its atmosphere, has a T_{eff} of 950 ± 50 K, and a surface gravity of $10^{5.0 \pm 0.5}$ cm s^{-2} [18,20]. Hence, it is unambiguously substellar. Gl229B has been observed from 0.65 to 10 microns, and its spectrum includes features due to H_2O, H_2, cesium [21], and CO [22]. It shows no signs of TiO, VO, FeH, or CaH (classic constituents of M dwarf atmospheres). From theory [17,18], we expect that metals that can make silicates at temperatures of 1500 to 2500 K are sequestered well below the photosphere. However, other less refractory species may have condensed in Gl229B's atmosphere (Sharp *et al.*, in preparation). The observed [23] suppression of the optical flux hints at this, as does the shallower than predicted near–IR troughs and the excess flux near 1 micron in models without clouds or hazes. Further progress in brown dwarf/giant planet theory hinges upon a resolution of the role of clouds/grains in spectrum formation. From the work of Lunine *et al.* [24] and of Burrows *et al.* [14], we already suspect that additional opacity due to silicate, corundum, and iron grains has lowered the edge object's mass, luminosity, and effective temperature. Below 1200 K, other species will assume new importance [17,25]. Figure 1 depicts the chemical equilibrium species for phorphorus as a function of atmospheric temperature in a representative model of Gl229B. Such transitioning with altitude from one dominant species to another is a central feature of these cool atmospheres for most of the major elements. Note that even $Mg_3P_2O_8$ condenses at the lower temperatures in the figure. This is not unexpected, since the atmospheres of brown dwarfs and EGPs provide us with low–temperature environments in which even quite non–refractory species can condense. In the much hotter stars, the constituent elements of these molecular species remain atomic and in the gas phase.

IV. EXTRASOLAR PLANETS/BROWN DWARFS DISCOVERED VIA DOPPLER SPECTROSCOPY

The world was surprised by the discovery of a companion to 51 Peg with an $m sin(i)$ of 0.47 M_j and an orbital semi–major axis (a) near $\sim$ 0.05 A.U. [8,9]. 51 Peg b is one *hundred* times closer to its primary than is Jupiter, but its discovery was only the first of a whole new class. To date, $\sim$20 substellar objects have been identified via high–resolution Doppler spectroscopy with

m$sin(i)$s from 0.45 M_j to 50 M_j and as between 0.04 and 4 A.U. (M. Mayor, this volume). These characteristics were wholly unanticipated and challenge the theory of star and planet formation, while energizing the embryonic theory of their colors, spectra, and thermal evolution. Despite its proximity to 51 Peg a, 51 Peg b's gravitational potential is deep enough to enable it to survive for a Hubble time [19]. Its inferred T_{eff} is 1200–1500 K and we would expect clouds of silicates, sulfides, iron, *etc.* to factor into its optical albedo in a feedback loop. 55 Cnc b, HD114762 b, 70 Vir b, 47 Uma b, υ And b, and τ Boo b will have T_{eff}s from 200 K to 1500 K and, hence, may represent the entire range of profiles and compositions we will be studying in the near future. Be they "planets" formed from protostellar disks or "brown dwarfs" formed directly via the process of star formation, extrasolar substellar objects with molecular atmospheres and T_{eff}s from Saturn's (95 K) to Gl229B's (950 K) and τ Boo b's ($\sim$ 1500 K) are only now getting the warranted theoretical attention. In a given EGP or brown dwarf, there may be many cloud decks with different compositions. This possibility is both daunting and exciting for the modeler.

We have recently completed the first in a series of studies of the colors and spectra of objects with T_{eff}s below 1300 K, molecular atmospheres, and high gravities [17]. There are a few unique aspects of such EGP/brown dwarf atmospheres that bear listing. Below T_{eff}s of 1300 K, the dominant equilibrium carbon molecule is CH_4, not CO, and below 600 K the dominant nitrogen molecule is NH_3, not N_2. The major gas–phase opacity sources are H_2, H_2O, CH_4, and NH_3. As stated above, for T_{eff}s below $\sim$400 K, water clouds form at or above the photosphere and for T_{eff}s below 200 K, ammonia clouds form. The variety of sulfide, chloride, and phosphorus–bearing clouds that will form at other pressure and temperature levels should alter the total opacities and the extent of convective zones in significant ways yet to be determined. Collision–induced absorption of H_2 partially suppresses emissions longward of $\sim$10 microns. The holes in the opacity spectrum of H_2O that define the classic telluric IR bands also regulate much of the emission from EGP/brown dwarfs in the near infrared. The windows in H_2O and the suppression by H_2 conspire to force flux to the blue for a given T_{eff}. This effect is altered if gas–phase H_2O condenses into H_2O clouds. Generally, what results is an exotic spectrum enhanced relative to the blackbody value in the J and H bands ($\sim$1.2 microns and $\sim$1.6 microns, respectively) by from two to ten orders of magnitude, depending upon T_{eff} and the true role of clouds. Figures 2 & 3 depict low–resolution theoretical infrared spectra for a variety of masses at 1 Gyr age and for a "Jupiter" at a variety of ages. As T_{eff} decreases below $\sim$1000 K, the flux in the M band H_2O window ($\sim$5 microns) is progressively enhanced relative to the blackbody value. Hence, the J, H, and M bands are the premier bands in which to search for cold substellar objects. The Z band ($\sim$1.05 microns) is also super–blackbody over this T_{eff} range. Eventhough K band ($\sim$2.2 microns) fluxes are generally higher than blackbody values, H_2 and CH_4 absorption features in the K band decrease its importance *relative*

to J and H. As a consequence of the increase of atmospheric pressure with decreasing T_{eff}, the anomalously blue $J-K$ and $H-K$ colors get *bluer*, not redder. Hence, some M dwarf colors are repeated in the substellar realm and the infrared HR diagram can be *double-valued.*

The enhancements we predict in the near infrared, verified a posteriori for Gl229B, will make the variety of searches for substellar objects now being undertaken in the field and around nearby stars easier than first feared. Platforms such as NICMOS [28], NGST, ISO [29], SIRTF [30], Gemini/SOFIA [31,32], the VLT (F. Paresce, this volume), and the LBT [33] and the DENIS and 2MASS surveys have detection ranges that encompass volumes that are ten to one thousand times the volumes estimated under the blackbody assumption. The only essential for the continued health and expansion of this new science is that substellar objects exist in respectable numbers. This remains to be seen.

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FIGURES

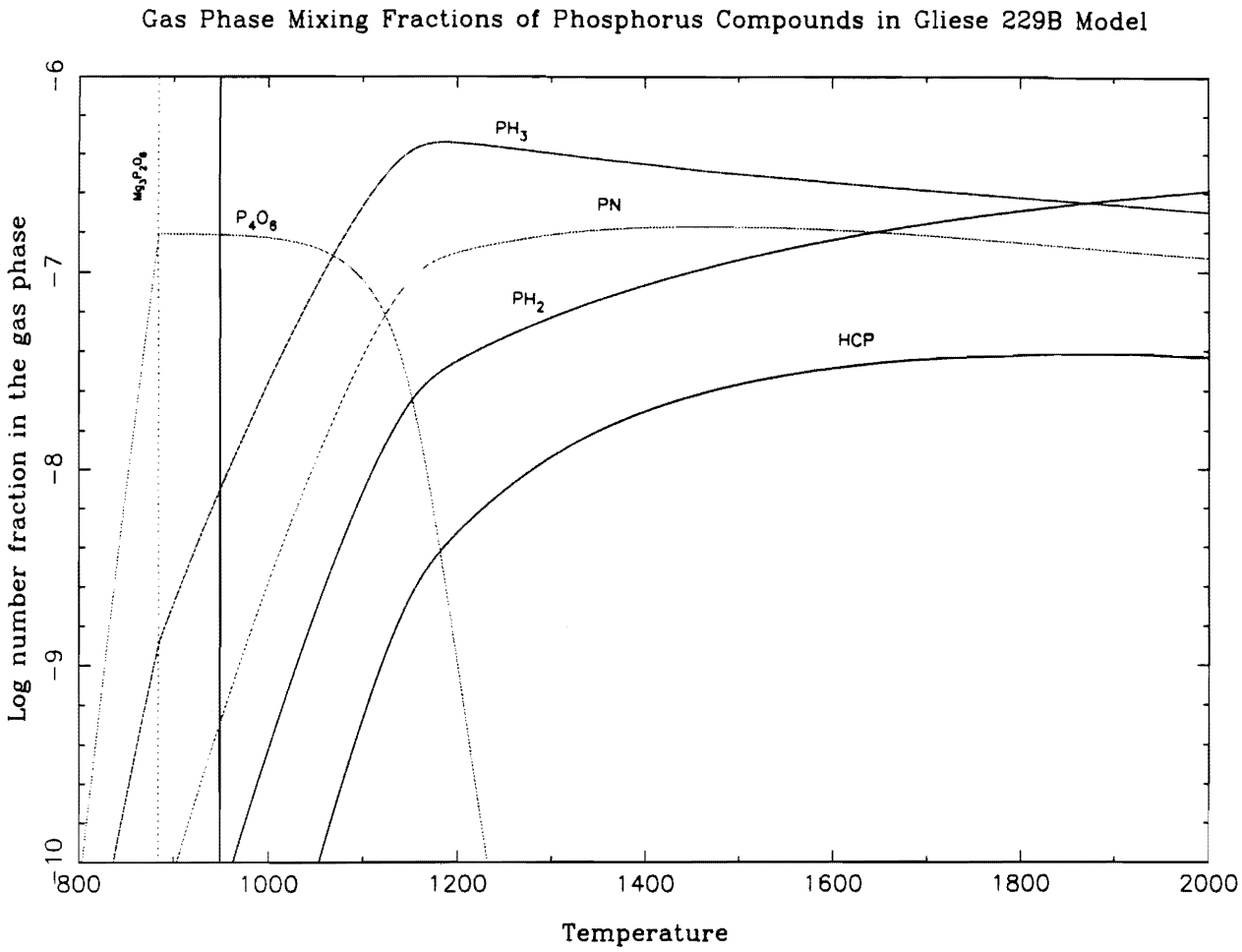

FIG. 1. Gas–phase mixing fractions of some phosphorus compounds for a model of Gl229B's atmosphere with a T_{eff} of 950 K (solid vertical line) and a gravity of 10^5 cm s^{-2}. Note the formation and condensation of $Mg_3P_2O_8$ just below 900 K. This molecule may become the dominant reservoir of phosphorus at low temperatures (however, see Sharp *et al.* 1998).

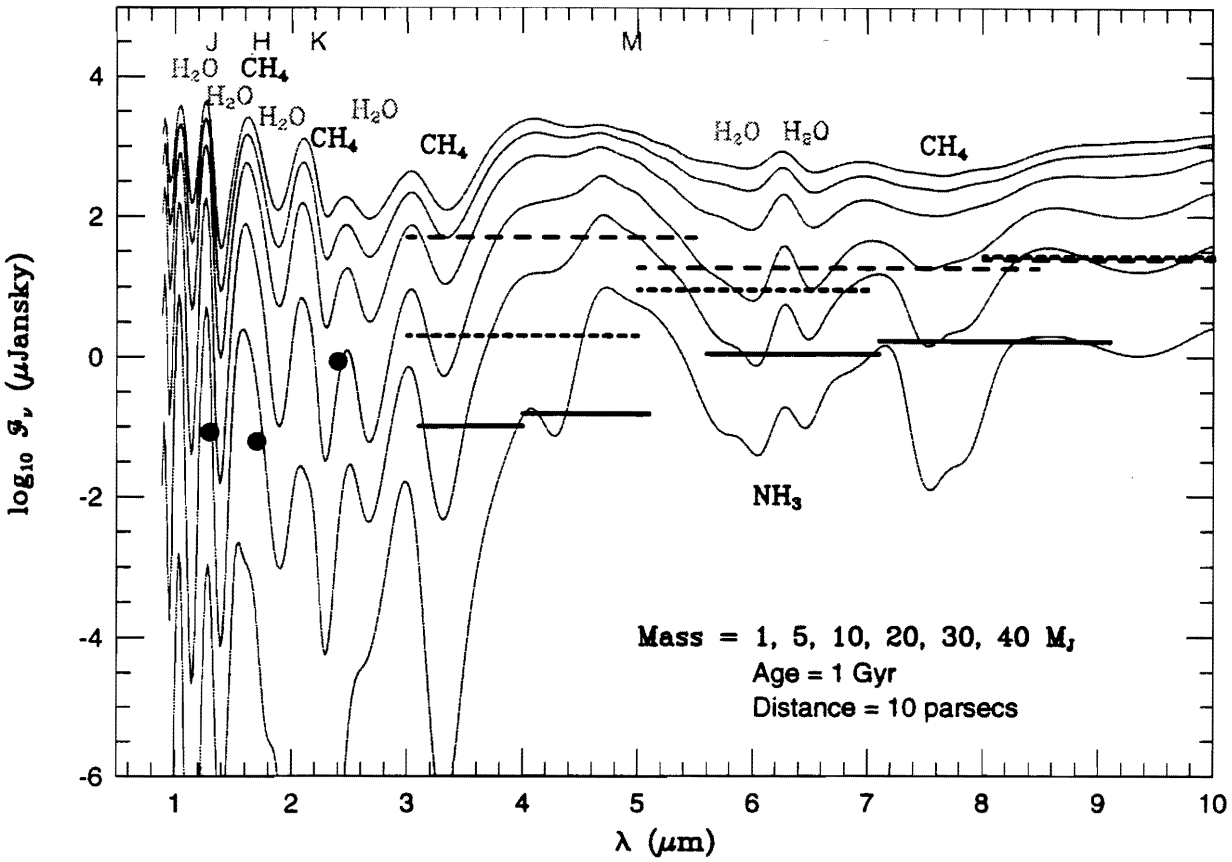

FIG. 2. The flux (in μJanskys) at 10 parsecs versus wavelength from 1 micron to 10 microns for 1, 5, 10, 20, 30, and 40 M_J models at 1 Gyr. Shown are the positions of the J, H, K, and M bands and various molecular absorption features. Also included are the putative sensitivities of the three NICMOS cameras, ISO, Gemini/SOFIA, and SIRTF. NICMOS is denote with large black dots, ISO with thin, dark lines, Gemini/SOFIA with thin, light lines, and SIRTF with thicker, dark lines. At all wavelengths, SIRTF's projected sensitivity is greater than ISO's. SOFIA's sensitivity overlaps with that of ISO around 10 microns. For other wavelength intervals, the order of sensitivity is SIRTF > Gemini/SOFIA > ISO, where > means "is more sensitive than."

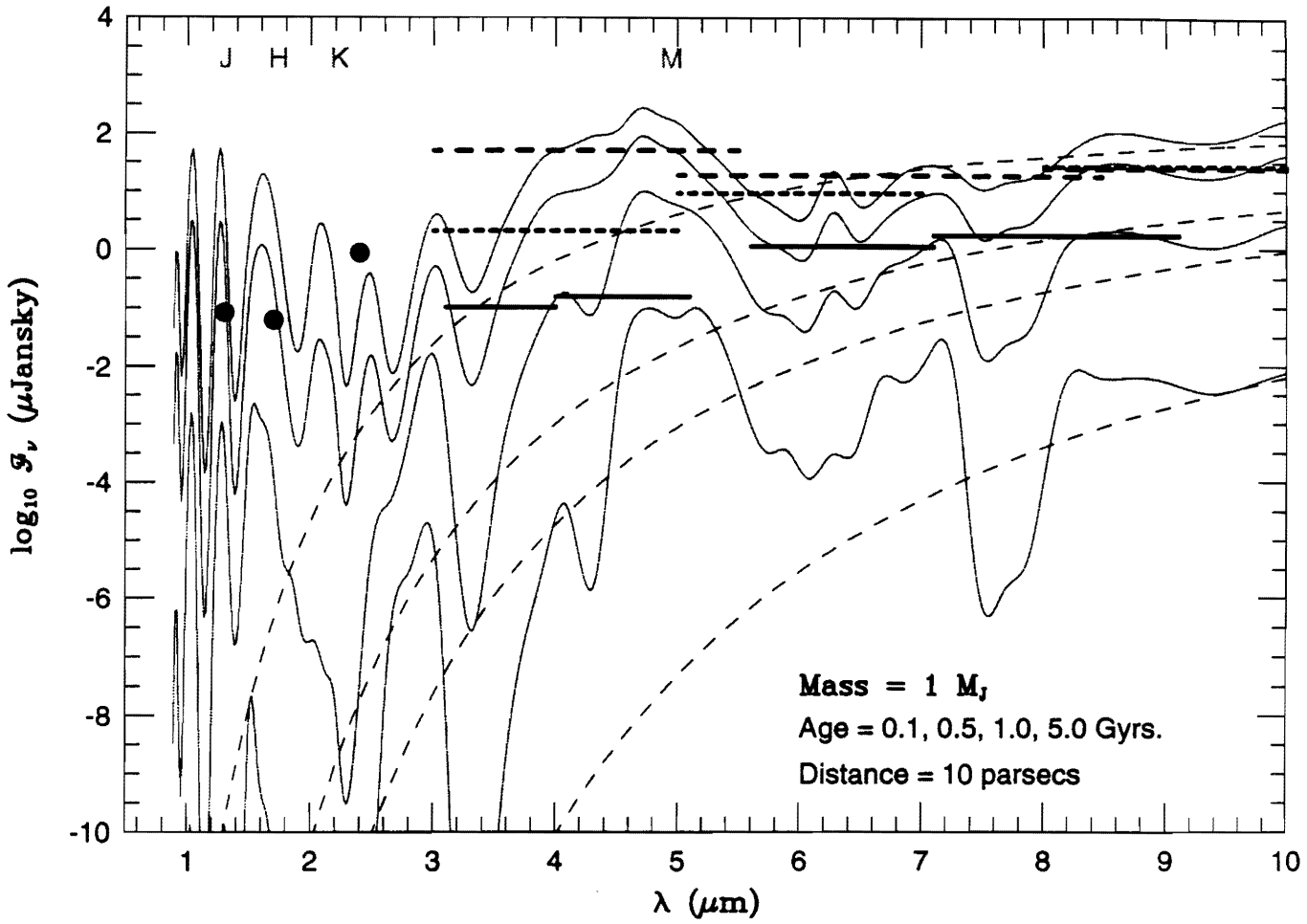

FIG. 3. The flux (in μJanskys) at 10 parsecs versus wavelength (in microns) from 1 micron to 10 microns for a $1\,M_J$ object at ages of 0.1, 0.5, 1.0, and 5.0 Gyr. Superposed are the positions of the J, H, K, and M bands and the corresponding blackbody curves (dashed), as well as the estimated sensitivities of the three NICMOS cameras, ISO, Gemini/SOFIA, and SIRTF (see caption to Figure 2).