A Search for Pulsation in Young Brown Dwarfs and Very Low Mass Stars

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Abstract

In 2005, Palla & Baraffe proposed that brown dwarfs and very low mass stars (<0.1 solar masses) may be unstable to radial oscillations during the pre-main-sequence deuterium burning phase. With associated oscillation periods of 1–4 hours, this potentially new class of pulsation offers unprecedented opportunities to probe the interiors and evolution of low-mass objects in the 1–15 million year age range. Furthermore, several previous reports of short-period variability have suggested that deuterium-burning pulsation is in fact at work in young clusters.

For my dissertation, I developed a photometric monitoring campaign to search for low-amplitude periodic variability in young brown dwarfs and very low mass stars using meter-class telescopes from both the ground and space. The resulting high-precision, high-cadence timeseries photometry targeted four young clusters and achieved sensitivity to periodic oscillations with photometric amplitudes down to several millimagnitudes. This unprecedented variability census probed timescales ranging from minutes to weeks in a sample of 200 young, low-mass cluster members of IC 348, Sigma Orionis, Chamaeleon I, and Upper Scorpius. While I find a dearth of photometric periods under 10 hours, the campaign's high time resolution and precision have enabled detailed study of diverse light curve behavior in the clusters: rotational spot modulation, accretion signatures, and occultations by surrounding disk material. Analysis of the data has led to the establishment of a lower limit for the timescale of periodic photometric variability in young low-mass and substellar objects, an extension of the rotation period distribution to the brown dwarf regime, as well as insights into the connection between variability and circumstellar disks in the Sigma Orionis and Chamaeleon I clusters.

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Chapter 1

Introduction

Stars and brown dwarfs in the ~1–10 million year (Myr) age range occupy a pivotal position in the stellar evolution sequence, characterized by emergence from molecular cloud birthplaces, ongoing dissipation of primordial circumstellar disks, and assembly of planet systems. The evolutionary stage also involves dramatic changes in internal structure as well as radius and angular momentum. Stellar and circumstellar phenomena during this epoch are interconnected, through deposition of accreting material onto the central object, as well as transfer of angular momentum to the surrounding disk. How do these processes operate together to determine the eventual structures and distributions of (sub)stellar objects? The holy grail of brown dwarf (BD) and star formation studies is a unified model incorporating the physics of gravitational collapse, outflow, gas accretion, disk structure and chemistry, magnetic field configuration, and angular momentum transfer, all coupled with stellar evolution. Today, many components of this model exist, but the linkages remain weak and the details scarce.

Theoretical understanding of young, low-mass objects and their environments has long progressed hand in hand with observation. Our current picture of the first few Myr of the stellar or substellar life cycle has been established in large part through dedicated surveys of young clusters. Extensive, unbiased studies of known members are crucial for assessment of the initial mass function, angular momentum, and spatial aggregation that are thought to bear the imprint of the formation process. With a number of young stellar associations now identified at ages of 1–10 Myr, comprehensive censuses provide statistically meaningful data on the characteristics of low-mass populations, including hundreds of brown dwarfs. Although the physics governing their early evolution remains difficult to probe directly, both the global observational properties as well as accompanying variability offer valuable tracers of the various underlying phenomena at work.

Data derived from temporal variability studies complement single-epoch surveys of stellar populations spanning a range of spectral types and ages in nearby young clusters by contributing information on changes occurring much faster than the evolutionary timescale. A major aim of this thesis work is to show how high-precision, high-cadence optical and infrared photometric monitoring can open up new avenues of research into young, very low mass stars (VLMSs; $\lesssim$0.1 $M_\odot$) and brown dwarfs. In the coming sections we will review the present understanding of these objects and their environments, open questions, and how time series observations can illuminate some of these problems.

1.1 State of the knowledge on young brown dwarfs and very low mass stars

1.1.1 Interior and evolution models

Much of the modeling efforts to date on young BDs and VLMSs has focused on predicting their interior and overall properties, such as mass and radius, as a function of age. The main theoretical difficulty is that the physics relevant to these objects is far from that of a simple gas or solid. With a combination of cool, dense outer layers and hot, degenerate centers, brown dwarfs have non-trivial equations of state (Saumon et al. 1994) and low-temperature opacities. The treatment of convection adds additional complications.

Despite numerous challenges, the science of low-mass stellar and substellar evolution has come a long way since the first structure models were produced decades ago by Hayashi & Nakano (1963) and Kumar (1963). On the pre-main sequence, gravitational contraction is a primary source of energy. Ultimately, the core either becomes hot enough to fuse hydrogen (stars with $M \gtrsim 0.075 M_\odot$) or dense enough for electron degeneracy to dominate pressure support ($M \lesssim 0.075 M_\odot$). The value of 0.075 $M_\odot$ is referred to as the hydrogen-burning minimum mass and sets the boundary between stars and brown dwarfs, the latter of which Kumar (1963) originally designated “black dwarfs.”

While the BDs may not burn significant hydrogen, they nevertheless have much in common with their stellar cousins. All objects on the pre-main sequence are fully convective, and those with spectral types M0 and later ($M \lesssim 0.5$ M$_\odot$) exhibit significant optical and infrared absorption due to the formation of molecules such as H_2O, TiO, VO, and other metal oxides in their atmospheres. At even cooler temperatures and older ages, grain formation becomes another important source of opacity. The accuracy of atmospheric models has increased greatly over the past 15 years (Allard et al. 1997; Burrows et al. 1997), with the inclusion of frequency-dependent absorption due to these molecular species as well as dust grain formation below ~2800 K. As a result, self-consistent models of the radiative properties of low-mass objects are now available and routinely output color-magnitude and color-color data in line with observations (Baraffe & Chabrier 2000; Burrows et al. 2001).

Deuterium burning, whereby ^{3}He is produced from ^{2}D, is another important piece of input physics at low mass and young ages. This process is more rapid than the p-p chain, and hence ignition can take place at lower temperatures, down to $4{\times}10^5$ K (Chabrier et al. 2000). When burning commences, it dominates the luminosity and temporarily halts gravitational contraction. Grossman & Graboske (1973) were among the first to determine that the minimum mass for this process is $\sim$0.012 $M_\odot$, although their estimates for the duration of burning were too large by an order of magnitude. Burrows et al. (1997) and Chabrier et al. (2000) later confirmed the mass limit, finding that 99% of deuterium is depleted within ~2 Myr for the 0.1 $M_\odot$ stars and within ~30 Myr for the 0.015 $M_\odot$ BDs. Objects with masses above 0.065 $M_\odot$ also have high enough interior temperatures ($> 2.5 \times 10^6$ K) to burn lithium as well (Chabrier et al. 1996).

Dantona & Mazzitelli (1985) were one of the earliest groups to present detailed pre-main sequence evolutionary models down to 0.04 $M_\odot$, incorporating appropriate equations of state, opacities, boundary conditions, and deuterium abundances. Current-generation models (e.g., D'Antona & Mazzitelli 1997; Baraffe et al. 1998; Siess et al. 2000; Burrows et al. 2003; Tognelli et al. 2011) have further refined equations of state along with non-grey atmospheres, and they now match observed temperature/luminosity data reasonably well (e.g., Luhman 1999). Young BDs and VLMSs have effective temperatures ranging from ~2400 to 3200 K, and estimated radii of ~0.5–0.8 $R_\odot$, although independent observational confirmation of this latter parameter is difficult. At ages of a few Myr, objects at the substellar boundary have luminosities of ~0.05 $L_\odot$, over 1.5 orders of magnitude larger than field objects of similar spectral type. After the exhaustion of deuterium, they eventually cool by a factor of 100–100,000, making detection more challenging.

1.1.2 Inventory of young BDs and VLMSs

The discovery and characterization of substellar objects in star-forming regions preceded that of the cooler field brown dwarfs, whose faintness precludes detection for all but the closest (i.e., within ∼50 pc). The first field brown dwarf, Gliese 229B, was discovered in 1995 by Nakajima et al. via coronographic imaging. BDs in young clusters, on the other hand, were long understood to exist as a natural extension of the initial mass function (IMF). It is in these molecular cloud regions that they are thought to form en masse, along with the higher mass stars. Prior to the advent of dedicated spectroscopic follow-up, many faint cluster objects were suspected to be substellar because of their red colors (e.g., Hillenbrand 1997; Luhman et al. 1997). Nevertheless, the first young BDs with confirmed spectral types of M6 and later were not identified until nearly two decades ago (e.g., Strom & Strom 1994, 's study of the Taurus-Auriga region).

Since then, surveys have uncovered over 500 substellar objects in young clusters and star-forming regions (see §2.1 and §2.2 for a discussion of the census), through wide-field optical and infrared imaging, detection of x-ray emission, proper motion measurements, and spectroscopic surveys for emission and youth-related features. Most of the discovered substellar objects lie in nearby low-mass star-forming regions, such as the Orion Nebula Cluster, ρ Ophiuchus, the Taurus-Auriga and Upper Scorpius associations, and IC 348. A variety of methods are at our disposal for confirming an object's cluster membership, most notably the identification of spectral lines consistent with youth (Li, Na, broad Hα emission) and the detection of infrared excess associated with a circumstellar disk. Particularly comprehensive surveys have typically involved initial photometric criteria for selection of young candidates, along with follow-up spectroscopy (e.g., Luhman 2007; Slesnick et al. 2008). Thanks to these surveys, data ranging from spectral types to accretion measures is widely available, and comparison of the observed effective temperatures and luminosities with theoretical structure and formation models is now feasible in many young clusters.

1.2 Open questions

The recent onslaught of data on young, low-mass cluster members has provided valuable feedback for modeling efforts. While the basic physics of convection, degeneracy, and pre-main-sequence contraction have been confirmed, there nonetheless remain substantial uncertainties related to the structure of young, very low mass objects and their immediate environments. Comparisons of parameters output by different low-mass evolution codes reveals significant discrepancies in the predicted Hertzsprung-Russell ("H-R") diagram positions (Gennaro et al. 2012). Yet with the relatively recent detection of hundreds of extrasolar planets around other stars, much of the detailed modeling has increasingly focused on much lower masses (i.e., $M_{\rm Jup}$–the mass of Jupiter–and below). The somewhat higher masses of brown dwarfs, along with the relatively youthful ages of star-forming clusters represent a different parameter space than those of planetary companions to field stars. Consequently, there are also different challenges to generating accurate models and determining the relevant input physics. We highlight here some of the primary–and often interrelated–questions surrounding young BDs and VLMSs that await explanation in the coming years.

1.2.1 Origins of brown dwarfs

Although the existence of brown dwarfs has been acknowledged for nearly two decades, how exactly they form remains a serious problem to explain. The standard picture of low-mass star formation entails gravitational collapse of unstable Jeans-mass (Jeans 1902) regions of molecular cloud where densities exceed a critical value. With typical Jeans masses of order 1 $M_\odot$, most star-forming clusters would not be expected to produce low-mass stars and brown dwarfs with masses an order of magnitude less that this value. It is nevertheless possible to extend the formation process well into the substellar regime by taking into account areas of much higher density, where the minimum mass for gravitational fragmentation can theoretically drop below 0.01 $M_\odot$ (Kumar 2003). However, the opacity of very low mass cores typically increases prohibitively during the collapse process, such that the resulting heating raises the Jeans mass and counteracts fragmentation. Compounding the issue of low-mass core formation is the accretion process. Hydrodynamic star formation simulations indicate that it is rare for a nascent BD to stop accreting material before it has reached stellar mass (Bate et al. 2003). Thus it is a challenge to contrive scenarios in which brown dwarfs could form directly from cloud fragmentation.

Three hypotheses have been proposed to explain this conundrum. First, the Jeans mass could lie well below 1.0 $M_\odot$. The theory used to estimate this value assumes spherical symmetry, whereas if objects form in elongated sheets or filaments of material, then they could potentially conglomerate at lower masses. This is the basis of the turbulent fragmentation theory (Padoan & Nordlund 2002; Hennebelle & Chabrier 2008), in which colliding flows of turbulent gas are entrained by magnetic fields to produce regions of high density necessary to form small cores. Reipurth & Clarke (2001), on the other hand, argued that cores destined to become stars may have their mass assembly cut off prematurely if they are dynamically ejected from a multi-body system. This process would halt accretion before an object has gathered enough gas to cross the substellar boundary. Whitworth & Zinnecker (2004) proposed a similar idea to produce brown dwarfs as a byproduct of star formation, through photoevaporation of massive cores.

An additional possibility for producing brown dwarfs is a planet-like formation scenario (Pickett et al. 2000). Whitworth & Stamatellos (2006) have successfully simulated the formation of BDs via gravitational fragmentation in the disks surrounding higher mass stars. The conditions for formation via this gravitational instability are a relatively massive disk and a cooling time comparable to the disk orbital timescale. Their radiative hydrodynamics code produces objects with typical masses $\sim$20–30 $M_{\rm Jup}$, many of which are subsequently ejected into the field to become isolated BDs.

It may in fact be the case that all three formation mechanisms are at work in star and BD-forming regions (Stamatellos & Whitworth 2011). Whichever modes are dominant has implications for the initial mass function (IMF) and multiplicity properties of brown dwarfs. Likewise, the observed properties of brown dwarfs–such as presence of disks, companions, accretion and outflows–provide opportunities to evaluate some of these theories.

1.2.2 Disks and accretion around brown dwarfs

Tied to the formation of brown dwarfs is the presence of disks of dust and gas encircling them. Since launch of the *Spitzer Space Telescope* in 2003 (Werner et al. 2004), mid-infrared photometry has been possible to the sensitivity level required for unambiguously detecting emission from warm dust around very low mass objects. Indeed, some of the first surveys with the *Spitzer* Infrared Array Camera (IRAC) Multiband Imaging Photometer (MIPS) and instrument revealed infrared excesses associated with a substantial fraction (40–50%) of substellar members of the young clusters IC 348 and Cha I (Luhman et al. 2005a). These data were interpreted to suggest that the disks fractions of young BDs are similar to those of the higher mass stars at the same age. Subsequent studies have detected such circumsubstellar disks in a number of other clusters, including σ Orionis, Taurus, Upper

Scorpius, and the TW Hydrae association (Scholz et al. 2007; Muench et al. 2007; Damjanov et al. 2007; Riaz & Gizis 2008; Luhman et al. 2008b,a; Riaz et al. 2009; Luhman et al. 2010)
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Not only do young brown dwarfs possess disks, but many also display signatures of active accretion from them, whether through strong emission lines, photometric variability, or even spectroscopic jets and outflows (Whelan et al. 2005, 2009). This evidence can be used to argue that BDs arise from the same formation processes as higher mass stars. But while the prevalence and phenomenology of disks may be similar above and below the substellar boundary, there is evidence for substantial variation of chemistry–and even planet-forming potential–with central object mass. Mass accretion rates decrease into the substellar regime, according to an approximate empirical correlation $M \propto M_*^2$ (Muzerolle et al. 2003; Mohanty et al. 2005). Recent theoretical work has furthermore suggested that this relation may be bimodal, and substantially steeper at very low mass (Vorobyov & Basu 2009). Observations of bulk disk properties also confirm that dust around BDs displays the grain growth and settling required for planet formation (Apai 2005), although the disks appear to be significantly flatter (i.e., more settled) than those in disks around higher mass stars (Szűcs et al. 2010). Further details on the distinct properties of circumsubstellar disks await discovery.

1.2.3 Interior and atmospheric physics

In addition to the difficulties in explaining the origins of BDs and surrounding disks, there are many gaps to fill in our knowledge of the early stages of their evolution. Theoretical models (Burrows et al. 1997; Baraffe et al. 2003) are moderately successful in reproducing the observed properties of BDs and VLMSs, at least at intermediate and old ages Burrows et al. (2001). Such models can be used to estimate fundamental parameters, namely mass and age. However, they have not been extensively tested by independent measurements of these parameters, nor do they account in detail for more complex realities such as magnetic fields and rotation which can have significant effects as illustrated for very low mass stars by D'Antona et al. (2000). Furthermore, below ages of 5 Myr and masses of 0.5 $M_\odot$, substantial uncertainties in the initial radii and accretion history as well as the convection efficiency, low-temperature opacity, and equation of state of these objects hamper theoretical modeling efforts (Baraffe et al. 2002).