Astro2020 Science White Paper

Mapping Ultracool Atmospheres:
Time-domain Observations of Brown Dwarfs and Exoplanets

Thematic Areas: ■ Planetary Systems ■ Stars and Stellar Evolution

Principal Author:
Name: Dániel Apai
Institution: Steward Observatory and Lunar and Planetary Laboratory, The University of Arizona
Email: apai@arizona.edu
Phone: 520-621-6534

Co-authors:
Beth Biller (University of Edinburgh), Adam Burgasser (University of California, San Diego), Julien H. Girard (Space Telescope Science Institute), John E. Gizis (University of Delaware), Theodora Karalidi (University of Central Florida), Adam L. Kraus (UT-Austin), Ben W. P. Lew (Lunar and Planetary Laboratory, University of Arizona), Elena Manjavacas (W. M. Keck Observatory), Mark Marley (NASA Ames Research Center), Paulo A. Miles-Páez (The University of Western Ontario), Caroline V. Morley (University of Texas, Austin), Jacqueline Radigan (Utah Valley University), Johanna M. Vos (American Museum of Natural History), Yifan Zhou (University of Arizona

Abstract: Ultracool atmospheres (brown dwarfs, directly imaged exoplanets, close-in and transiting gas giants) are at one of the forefronts of modern astrophysics. In contrast to stellar atmospheres, these ultracool atmospheres are strongly influenced by condensate clouds, complex chemistry, and sometimes by external irradiation. As for stars, the photospheric temperature is the primary parameter that sets the properties of these atmospheres, but multiple secondary parameters also influence them. These secondary parameters are often degenerate in their effects, making it difficult to disentangle and test models describing them. Furthermore, multiple lines of evidence demonstrates that ultracool atmospheres are often heterogeneous and, therefore, not accurately described by one-dimensional models.

Over the past ten years a rapidly expanding body of time-domain, high-precision observations began to provide spatial information (by utilizing the rotation of the targets). Spatial information is a game-changer for ultracool atmospheres for two reasons: First, they enable disentangling processes with otherwise degenerate effects on the hemisphere-integrated measurements. Second, they enable tests and improvements of two- and three-dimensional, time-evolving atmospheric models.

The most efficient pathway to understand ultracool atmospheres (gaseous exoplanets, brown dwarfs, planetary-mass companions, planetary-mass objects) is to adopt an integrative approach: combine information emerging from the different types of ultracool atmospheres into a single, general framework. We summarize here the variety of time-resolved observations that are expected to reshape our understanding of ultracool atmospheres in the next decade and identify some requirements for this progress.

RELATION TO THE NAS EXOPLANET STRATEGY REPORT: *This white paper focuses on an issue central to understanding exoplanet atmospheres, but which was not addressed in detail by the NAS Exoplanet Strategy Report.*

The field of ultracool atmospheres comprises of studies of objects that are studied via different techniques and may have formed differently, but share key atmospheric processes: brown dwarfs, directly imaged exoplanets, brown dwarf companions, planetary-mass objects, giant exoplanets. Understanding these ultracool atmospheres is one of the forefronts of modern astrophysics and one of the areas in which the next decade has the potential to bring transformational capabilities.

1 Key Questions

In the following we identify four key questions that are pivotal to our understanding of ultracool atmospheres:

(1) What is the Nature of Condensate Clouds? With temperature below 2,000 K ultracool atmospheres contain condensate particles. The particles' compositions range from the most refractory metal-oxides (in hottest atmospheres) through silicates (prominent in many of the currently observable atmospheres) to water ice (in the coolest known objects). Condensate grains have fundamental impact on the atmospheres: the condensation process itself removes gas-phase opacity and introduces continuum opacity, which may then limit the optical depths probed. Upper atmospheres rich in condensate grains will have pressure-temperature profiles different from condensate-free ones. Models and different lines of evidence suggests that condensate grains will form clouds, likely shaped by processes that are analogous to those seen in Solar System clouds: condensation/evaporation, gravitational settling, and mixing.

However, with the great diversity of ultracool atmospheres, it remains not well understood how our solar system-based cloud models can be applied to different types of ultracool atmospheres. It is not well understood, for example, in the case of multiple condensible species – whether should expect multiple thin cloud decks (each with a unique composition) or a single, thick cloud layers with mixed grain compositions.

(2) What are the Modes of Atmospheric Circulation? Atmospheric dynamics (including vertical mixing, presence of vortices, and large-scale circulation) plays important roles in modifying the pressure-temperature structure, opacity, and particle (cloud) distribution in ultracool atmospheres. Atmospheric circulation is the process in which hot jupiters differ most from brown dwarfs, planetary-mass objects, and directly imaged exoplanets. While the atmospheric circulation of hot jupiters is strongly forced, resulting in the presence of super-rotating equatorial jets that transport heat from the day to the night sides, the irradiation is typically negligible for directly imaged exoplanets, planetary-mass objects, and brown dwarfs. In the latter cases, the relative balance of the outward flow of the interior heat (from the objects' formation) and the object's rotation rate determine the regime of the atmospheric circulation.

(3) How does Atmospheric Chemistry Change with Fundamental Parameters? Ultracool atmospheres host complex chemical networks that determine the chemical composition of the atmospheres (including particles), opacity, the pressure-temperature profiles, and the emerging spectra. The atmospheric chemistry is impacted by fundamental parameters (temperature, bulk composition, surface gravity, irradiation) and it is also coupled to other processes (cloud formation/evaporation, atmospheric circulation, etc.). Over the past decades much progress has been made in modeling chemical networks in equilibrium, buy it is becoming clear that parts of the chemical networks in ultracool atmospheres are not well described by equilibrium chemistry. The sub-networks in question involve reactions between abundant species whose dynamic timescales are shorter than their kinetic timescales (i.e., gas parcels may be transported to regions with different pressure/temperature conditions faster than they can reach chemical equilibrium).

(4) How does Bulk Composition vary with Formation? Bulk composition has long been identified as an important source of information on the conditions in and composition of the region in which substellar objects formed. Unlike stars, substellar objects typically preserve their bulk chemical composition and thus act as chemical time capsules. It has been proposed that bulk elemental composition (e.g., C/O and Fe/H ratios, etc.) can reveal whether objects have formed in the inner or outer regions of protoplanetary disks or formed as a result of gravitational collapse. Elemental abundances could be also used to identify the subset of planetary-mass brown dwarfs that are, in fact, ejected massive planets. Deciphering the actual abundances has been, up to now, challenging. However, with the progress of atmospheric retrievals, improved understanding of molecular opacties, and very large, homogeneous, high-quality spectral libraries, we are entering an exciting era when the chemical diversity of ultracool atmospheres can be studied and compared to models.

1.1 Breaking Important Degeneracies with Spatial Information

Most ultracool atmospheres are shaped by processes that primarily depend on at least five key parameters (in order of likely importance): 1) Photospheric temperature; 2) Condensate clouds; 3) Deviation from equilibrium chemistry; 4) Bulk composition; 5) Surface gravity. In addition, for the hottest brown dwarfs (M/L spectral type transition) the atmospheric ionization levels are high enough to allow a coupling between atmospheric structures and the magnetic field, representing a sixth process shaping the atmosphere. A key limitation to testing, improving, and verifying atmospheric models is the fact that the effects of changes in some of these parameters are degenerate in terms of key observables: for example, variations in pressure-temperature profile, non-equilibrium chemistry, cloud base pressure level, vertical structure of the cloud cover, and surface gravity all have direct or indirect impact on the near-infrared colors of ultracool atmospheres. Furthermore, spatially heterogeneous structures – especially heterogeneous cloud cover – limit the validity of one-dimensional models. This poses an ultimate limit to the extent to which degenerate processes can be disentangled *without* spatial information.

Over the past decade – and mostly in the past four years – *high-precision time-resolved observations* have provided unique *spatial* information on ultracool atmospheres (see [5] and [3] for recent reviews). These measurements exploit the rotation of the objects to translate spatial information into temporal (photometric, spectrophotometric, spectroscopic, and polarimetric) modulations. Although there is very significant information loss when relying on hemisphere-integrated signal to probe spatial brightness distribution, even these relatively crude maps led to breakthroughs in disentangling otherwise degenerate processes.

2 Time-resolved Observations in the Next Decade

2.1 Photometry and Spectrophotometry

The majority of existing time-resolved observations are photometric or spectrophotometric in nature. These observations can be carried out on large samples of brown dwarfs, including very faint ones, often without highly specialized instrumentation. These surveys demonstrated that heterogeneous clouds are very common in brown dwarfs [8, 31], that the highest-amplitude variability occurs at the L/T transition [38], that cloud thickness variations drive variability [37, 1, 12, 9], that some objects display pressure-dependent longitudinal (3D) cloud structure [11, 6, 48], and that heterogeneous clouds are present from early L [18] to late-T dwarfs [11] (Manjavacas et al., submitted). Heterogeneous clouds have also been observed in likely planetary-mass objects, exoplanet analogs, and low-gravity brown dwarfs [4, 1, 7, 24, 46, 28, 47]. Given the extensive ground-based surveys that have already been carried out [37], it is likely that most cutting-edge photometric and spectrophotometric work in the future will be space-based. HST, Spitzer, and soon JWST will provide much greater photometric precision than typically achievable from the ground; in addition, they allow probing the atmospheres in absorption bands that are also present in the terrestrial atmosphere (e.g., water).

A particularly exciting direction will be to explore the coolest known brown dwarfs (Y dwarfs) to study condensate clouds in their atmospheres [34, 42, 15, 23, 16, 36]. As these very cold (typically $< 600\ K$) atmospheres must be studied at long wavelengths ($> 2\mu m$), JWST will be a unique facility to obtain time-resolved spectrophotometry for them.

2.2 High-Contrast Time-resolved Spectrophotometry

High-precision photometry and spectrophotometry *combined* with high-contrast imaging or spectroscopy is enabling access to ultracool companions of stars – including planetary-mass brown dwarfs, planetary mass objects, and giant exoplanets. These observations have been demonstrated on HST/WFC3, providing information on condensate clouds in low- and intermediate gravity atmospheres [50, 51]. Multiple groups are making concentrated efforts into developing methodology to enable time-resolved photometry with Extreme Adaptive Optics systems [22, 2]. This is a field that is set for rapid expansion in 2020s due to the steadily increasing number of targets (directly imaged exoplanets) and the continuing improvement in facilities and methodology. WFIRST, JWST, and, in particular, 30m-class telescopes with extreme adaptive optics systems, will produce powerful maps of exoplanets and planetary-mass companions. Simultaneous observations with multiple facilities will be particularly valuable in developing multi-layer atmospheric maps – similar to but extending on work done through coordinated HST–Spitzer observations [11, 48].

2.3 Multi-rotational Photometric Monitoring

A lightcurve that covers a single rotation can be reproduced by an infinite number of surface brightness distributions on a rotating object. Simple assumptions on the allowable features (e.g., elliptical spots or bands) greatly reduce the number of allowable models; however, degeneracies remain. The next major step in reducing the family of acceptable models is by modeling the surface brightness evolution that occurs during multiple subsequent rotations – in these cases physically-motivated priors on the evolution of surface features further reduce model degeneracies. For example, the exclusion of super-sonic motions poses a very strong constraint on the surface brightness distribution and atmospheric circulation. In practice, three or more complete rotations greatly reduce the allowed range of possible solutions for the surface brightness distributions.

As of now very few observational programs could provide monitoring over multiple rotations, but these datasets have proved to be uniquely valuable in breaking degeneracies in surface brightness distribution and time-evolution. In [2] a large monitoring campaign with the Spitzer/IRAC camera provided lightcurves of 32 complete rotations for six brown dwarfs, along with simultaneous HST spectral mapping for a subset of rotations. This comprehensive database excluded elliptical spots as primary atmospheric brightness features and showed, instead, that L/T brown dwarfs sport zonal circulation and planetary-scale waves that are visible through their modulation of the cloud thickness.

Major progress can be made in the next decade by significantly extending multi-rotational (medium- and long-term) monitoring programs, essential for understanding the connections between atmospheric circulation, planetary waves, and their relation to condensate clouds are understood. Infrared telescopes or a world-wide network of sensitive ground-based infrared telescopes will be important to allow long-term monitoring of the most interesting objects.

2.4 Doppler Imaging and Polarimetry

In the Doppler imaging technique high spectral resolution, time-resolved spectroscopic observations are used to measure line profile changes over timescales comparable to the rotational period. As any local variation in surface brightness will modulate a specific radial velocity component of the rotating atmosphere, individual features will introduce time-dependent line shape modulations. A method that has been successfully applied to active stars to gain spatial information, it has an exciting potential for mapping ultracool atmospheres.

As of now, however, Doppler imaging has been demonstrated on a single brown dwarf target (Luhman 16B) that is ideally suited for the observations. These observations provided two-dimensional constraints on the heterogeneity of the cloud cover [14] and led to a map that was consistent with models based on HST spectrophotometry [20]. Currently, Doppler imaging of brown dwarfs is primarily limited by wavelength range of the near-infrared high-resolution spectrographs and by the light-collecting power of the largest telescopes [13].

In the next decade somewhat larger samples of targets will be accessible by broad wavelength-range (J–Ks band) spectrographs (e.g., CRIRES+, Kec/NIRSPEC, MMT/MAPS) that can combine signal from hundreds of spectral lines [13]. However, 30m-class telescopes are required to study statistically meaningful samples (dozens) of brown dwarfs.

Polarimetry: Single scattering by particles – such as dust grains – linearly polarizes light. If ultracool atmospheres have non-spherical grains with preferential orientation will show net polarization signal. In addition, light scattering efficiency and the phase function depends on the grain size, shape, and wavelength of the light. Time-resolved polarimetry can, therefore, provide information on the spatial distribution, sizes, and shapes of particles in ultracool atmospheres [30]. The initial exploration of the polarimetric variability have been encouraging [19, 32] but often limited by the telescope's light-collecting area and polarimetric stability. Polarimetry combined with time resolved photometry can also reveal information on quasi static bands (like Jupiter) and/or oblateness (Millar-Blanchaer et al., submitted).

Arguably, both polarimetry and Doppler imaging require a new generation of telescopes to reach their potential: Time-domain studies of rotational modulations require high signal-to-noise ratio measurements with short integration times: signals are typically percent level and must be sampled 10–100 times during one rotational period (typically 2–10 hours). Expanding the very small set of brown dwarfs and planetary-mass objects that can be studied via Doppler imaging as well as the signal-to-noise ratio of the Doppler maps **will require 30m-class** ground-based telescopes with high spectral resolution in the near-infrared wavelength regime. are essential to enhance the target samples to meaningful numbers for these methods.

2.5 Advanced Models

Radiative Transfer, Chemistry, Clouds, and Composition: Fully interpreting the spatial information gleaned from the time-domain observations is not possible without expanded modeling efforts. Specifically, one-dimensional models (forward models and retrievals) will be inherently insufficient. Our community will need to expand on the important first steps undertaken to create 1D+1D models (coupled 1D models representing atmospheric structures) [29, 37, 1, 33, 10].

A particularly important question that can be answered in the 2020s is the diversity of the bulk composition of ultracool atmospheres. Important compositional information (e.g., C/O ratio, relative water abundance, Na and K abundances) can be determined via atmospheric retrievals applied to well-understood and highly precise data [25, 26, 27, 35]. Time-resolved spectrophotometry is an extremely strong basis for such studies: the spatial information allows constraining condensate cloud properties, while the combined extremely high SNR (often SNR>1,000) makes retrievals particularly powerful. Therefore, the next decade will bring about major advances in atmospheric models, enabled by the rapidly expanding scope of observations and the superior data quality.

Atmospheric Dynamics: With the advent of time-resolved, high-precision measurements and the thus emerging spatial information, the predictions of detailed atmospheric dynamics models can now be directly compared to observations. First principles-based models (e.g, shallow water approximation [49]) have been successfully utilized to explore the principal modes of heat transport and circulation. These models showed that depending on the rotation rate and vertical heat transport rate, zonal circulation or localized vortices may dominate the longitudinal and vertical heat transport. More detailed global circulation models offer more realistic description for atmospheric temperature and brightness distributions [39, 40, 44, 45].

In the next decade, with the increasing wealth of spatial information, the importance of detailed atmospheric dynamics simulations is set to grow rapidly. It is important that funding opportunities are available to support the research that will lay the groundwork to enable the interpretation of time-resolved observations.

2.6 Solar System Analog Observations

Observations of Solar System planets provide powerful datasets to test the methods and assumptions used in translating time-domain information on ultracool atmospheres to spatial information [21, 43, 41, 2, 17]. Unfortunately, surprisingly few Solar System objects have been observed in ways that is useful for such studies: The typical requirements are high-precision disk-averaged photometry/spectrophotometry obtained over at least one complete rotation. Datasets with simultaneous spatially resolved information (detailed images) are especially valuable, as they allow direct identification of lightcurve features to atmospheric features. It is essential to expand on the time-resolved observations of Solar System planets. Of particular importance are high-resolution thermal infrared imaging of Jupiter, Saturn, Uranus, and Neptune, which are the closest analogs to the infrared measurements Spitzer, HST, and JWST are obtaining for ultracool atmospheres. Furthermore, reflected light high-resolution images will be essential to interpreting potential WFIRST time-resolved photometry of giant exoplanets.

2.7 Integrative Approach to Ultracool Atmospheres

Studies of hot jupiters, directly imaged exoplanets, planetary-mass objects, and brown dwarfs are exploring identical or very similar questions: typically the same physical/chemical processes in different, but overlapping regions of the parameter space. As of now, these sub-fields remain somewhat disconnected: brown dwarfs are often part of the stellar topical panels and categories, but they should be mostly seen as part of the spectrum of ultracool atmospheres. It is important that there are no artificial boundaries splitting this community but rather that the funding and review panels adopt an integrative approach.

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