Astro2020 Science White Paper

Dynamical Processes in the Planet-Forming Environment

Thematic Areas: ☐ Planetary Systems ☒ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

Principal Author:
Name: Peregrine M. McGehee
Institution: College of the Canyons
Email: peregrine.mcgehee@gmail.com
Phone: +1 (626) 993-4199

Co-authors:
Alan Boss (Carnegie Institute of Washington), Laird Close (University of Arizona), Sarah Dodson-Robinson (University of Delaware), Dimitri Mawet (California Institute of Technology), Andrew Szentgyorgyi (Harvard-Smithsonian Center for Astrophysics)

Abstract: The transfer of circumstellar disk mass and momentum onto the protostar and out into the environment occurs via a variety of mechanisms including magnetospheric accretion, jets, outflows, and disk winds. The interplay of these processes determine both the conditions under which planet formation occurs and the lifetime of the disk. Metallic emission lines, along with the Balmer series of hydrogen, probe the kinematics of gas within the planet-forming and central regions of circumstellar disks. High-spectral resolution study of these emission lines provides critical information on mass and momentum loss, turbulence, and disk wind origins.

1 Introduction

The formation process of planets is constrained by the kinematics within the inner circumstellar disk. Indeed, current models of protoplanetary disk evolution suggest that the lifetime of the disk in the planet-forming region is mainly defined by viscous evolution (accretion of gas onto the central star) and photoevaporation driven winds (heating of disk gas to thermal escape velocities by the central star) (Pascucci et al., 2011). In this science white paper we describe how sensitive and high spectral resolution studies of Balmer and metallic emission lines reveal critical insights into the planet forming environment including mass and momentum loss, turbulence, and disk wind origins. In particular we examine the significant information found by detailed observations of optical forbidden lines. Additional optical spectral features arising in the star–disk environment include Balmer and metallic emission lines arising from magnetospheric accretion columns and forbidden emission lines generated in the shocked regions associated with jets and outflows.

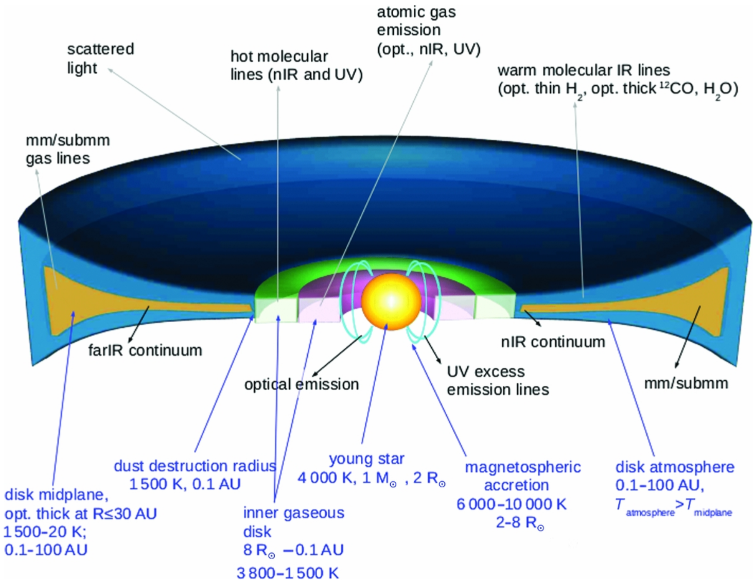

Figure 1: From Sicilia-Aguilar et al. (2016). A cartoon of the observations and the parts of the disk that they trace, taking as example a young solar analogue. Although observations trace very different regions and processes in the disk, we need to keep in mind that they are all connected through the disk itself. Note that the complexity of the disk is highly reduced for clarity (for instance, not all the tracers become optically thick at the same location/depth). Not to scale.

In their in-depth consideration of multi-wavelength studies of circumstellar disks, see Figure 1, Sicilia-Aguilar et al. (2016) point out that optical spectroscopy is well suited to target the physics of accretion, photoevaporation, outbursts, activity, and binarity. Within the set of *Burning Questions* listed by Haworth et al. (2016) in the context of **Grand Challenges in Protoplanetary Disc Modelling**, those addressable by optical studies include:

- What are the main drivers of global disc evolution? In particular, what is the main driver of the mass accretion rate in protoplanetary discs?
- Alongside magnetic fields, what other processes govern or control the launching of jets and outflows?

- What is the effect of environment on protoplanetary disc evolution? For example, discs close to O stars are clearly heavily disrupted by high energy photons (we observe such systems as proplyds), but what is the role of comparatively modest radiation fields?
- What are the possible initial conditions of class I/II/III discs and how do they influence the subsequent evolution? In particular, how does the early evolution of discs affect the chemistry and grain distribution? What is inherited from the star-formation process?
- How turbulent are protoplanetary discs?
- What is the process by which a protoplanetary disc becomes a debris disc? Transition discs; those with inner holes, are typically attributed to the action of photoevaporation by the host star, or planets. But which, if either, of these is the dominant process? Are there other processes that contribute significantly to disc dispersal, such as magneto-thermal winds? What are the initial conditions of debris disc models?

The profiles of forbidden emission lines arising from circumstellar disks can be decomposed into separate low and high velocity components, of which the former can be interpreted following Simon et al. (2016) as a combination of a narrow and broad Gaussian features (Figure 2). The high-velocity component (HVC) is typically blueshifted by 50–200 km s^{-1} with respect to the stellar velocity and **traces collimated jets** that have been spatially resolved at distances from 50 to several 100 AU from the star. The LVC is formed from a broad, centrally peaked component attributed to **gas arising in a warm disk surface in Keplerian rotation** (with FWHM between 40 and 60 km s^{-1}) and a narrow component (with FWHM $\sim$10 km s^{-1} and small blueshifts of $\sim$2 km s^{-1}). The narrow component **arises in a cool ($<$ 1000 K) molecular wind** as the peak velocities of various forbidden lines are inversely proportional to their respective critical densities – as expected where the flow accelerates as it rises from the disk.

2 Main Science Themes

The phenomena associated with the inner disk and circumstellar environment impact the planet formation process in differing ways and have associated observational tracers accessible by optical spectroscopy. In this context we discuss magnetospheric accretion, disk winds, jets and outflows, and the shocked interaction regions between jets and the ISM.

2.1 Magnetospheric Accretion

The process of magnetospheric accretion transfers mass and momentum from the disk onto the star and directly affects the inner regions of the cirumstellar disk. The **central ($r < 0.1$ AU) regions** containing magnetospheric accretion columns and the launching sites of winds and collimated jets are probed by Balmer and forbidden metallic emission lines. Study of metallic emission lines, which all are velocity modulated due to the rotation of the star, shows that the narrow line components are produced in the post-shock region, while the broad components originate in the more extended, pre-shock material in the accretion column. Analysis of the time-dependent detailed profiles of emission lines associated with the accretion columns provide

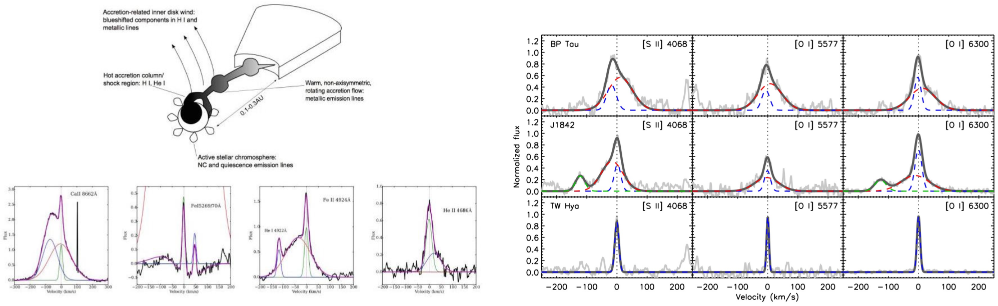

Figure 2: Examples of emission line observations probing accretion (*left*, from Sicilia-Aguilar et al. (2015)), and disk winds (*right*, from Fang et al. (2018)) physics, with the latter utilizing metallic forbidden lines. Lines associated with the magentospheric accretion column are shown here with decomposition into Gaussian components. The optical forbidden lines probing the disk wind and outflow launching environments, such as [S II] 4068Å, [O I] 6300Å, and [O I] 5577Å show distinct high and low velocity features.

insight into the details of the mass transfer due to magnetospheric accretion (Sicilia-Aguilar et al., 2015)

2.2 Disk Winds, Jets, and Outflows

Magnetohydrodynamic (MHD) and photoevaporative winds are thought to play an important role in the evolution and dispersal of planet-forming disks (Fang et al., 2018). These two wind mechanisms, along with possible MRI-driven turbulence, produce observational signatures due to structures in the outflow and the location of the wind launching radius. The dynamical feedback of magneto-hydrodynamic disk winds on the planet formation zone induces fast radial accretion and modification of planet migration (Frank et al., 2014).

The existence and character of magnetothermal winds are also uncertain. Theoretical studies predict that winds capable of driving disk accretion at the observed stellar accretion rates will be massive, with mass loss rates comparable to disk accretion rates. It has been suggested that the low velocity component of the [OI] 6300Å line emission from T Tauri stars provides evidence for magnetothermal winds (Simon et al., 2016). However, the decomposition of a complex [OI] 6300Å profile into multiple components potentially introduces uncertainty in the interpretation. More detailed studies of this and other diagnostics, combined with quantitative theoretical predictions of observable wind signatures can potentially verify the existence and angular momentum transport properties of magnetothermal winds.

MHD winds produce spiral structure in the outflows which present possible observational signatures that could detected similarly to spectroastrometry, targeting narrow forbidden O lines using multiple observations with different slit rotations. Constraining the wind launching radius by, e.g., identifying the Keplerian component to the line profile would also help distinguish between photoevaporation and magnetocentrifugal winds.

3-D modeling of non-ideal MHD disks (Suriano et al., 2019) reveals that disk and wind turbulence is suppressed by ambipolar diffusion with the result that laminar flow conditions likely dominate in the planet-forming region of 1–30 AU(Banzatti et al., 2019). However, neither mechanism (MRI or magnetothermal winds) has a verified observational signature although sisk turbulence possibly driven by the MRI has been detected both within 1 AU and beyond 40 AU. Within radii of 0.3 AU, high resolution spectroscopy of CO overtone emission has uncovered evidence for non-thermal velocities comparable to the sound speed in a few disk atmospheres consistent with the non-thermal motions expected for MRI-driven turbulence. Measuring the turbulence on the surface at $\sim$**1–5 AU** could help tell the difference between angular momentum transport by MRI and MHD winds (Najita & Bergin, 2018).

Emission line profiles result from the contributions of large scale bulk motion, e.g. from Keplerian orbits or outflows, thermal motion, and turbulence. Within the disk, the non-Keplerian contributions to the line broadening are, following Teague et al. (2016),

$$(\Delta v)^2 = \frac{2kT_{kin}}{\mu m_H} + \delta v_{turb}^2. \tag{1}$$

The use of relatively heavy molecules reduces the thermal component of the motion, for example millimeter-wave studies of CO Flaherty et al. (2018) find limits on the turbulent motion in the disk of TW Hya of $\sim 0.08c_s$, or 30 m s^{-1} at 140 AU. Elements heavier than CO, and thus would be suited for turbulence studies, that give rise to forbidden lines found in T Tauri disk optical spectra include Ca and Fe.

2.3 Jet Interactions with the Environment: Shocks

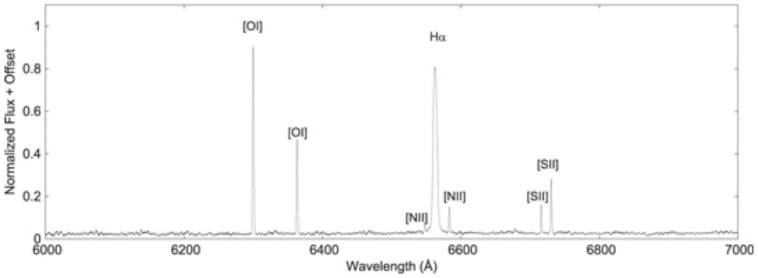

Figure 3: From Riaz & Whelan (2015). A portion of the R$\sim$40,000 VLT/UVES spectra for HH 1158 with the prominent accretion- and outflow-associated emission lines marked.

Warm outflow gas (10^3–10^4 K) is heated by internal shocks and moves at 10–100 km s^{-1} with acceleration seen within the **first 30 AU** (Schneider et al., 2014; Djupvik et al., 2016). The resulting jet–ISM shocked interaction regions, or Herbig–Haro objects, span hundreds of AU. Échelle observations of shock tracers revealed component FWHMs of 15–20 km s^{-1}. Detailed kinematic studies in optical forbidden lines such as [OI] 6300Å, [OI] 6363Å, [NII]6584Å, [SII] 6717Å, and [SII] 6731Å require resolutions better than 10 km s^{-1} (Davis et al., 2001).

3 Observations in the new era of ELTs

While exoplanets have been discovered at distances ranging from within 0.01 AU to 100s of AU from their parent stars, the studies of circumstellar disks to date have only provided detailed views exterior to the planet forming region. New frontiers in the planet formation science will be enabled by the high spectral and spatial resolution studies enabled by Extremely Large Telescopes (ELTs) such as the Thirty Meter Telescope (TMT) and the Giant Magellan Telescope (GMT). The upcoming generation of ELTs will bridge this gap and allow us to investigate the initial conditions, locations, and timescales of planet formation in a way not previously possible.

Optical spectroscopy with ELTS equipped with very high resolution spectrographs and ELTs of young stars and their disks benefits from the order of magnitude increase in sensitivity over existing 8 to 10 meter class facilities. Observations in the optical bands are constrained by natural seeing, with even Ground Layer Adaptive Optics giving no better than ∼0.25 to 0.40 arcseconds FWHM in the 400–1000 nm range. At the 140 pc distance to the Taurus SFR, this gives spatial resolutions of 35–60 AU. Spectra obtained centered on the young star will include lines from accretion, jets, and disk winds, providing a wealth of information about the immediate circumstellar environment and the planet forming environment.

The study of emission lines giving state of the art accretion and wind diagnostics drive spectral resolution requirements. These lines include both broad- and narrow-line features requiring R $> 50,000$ to study line profile variability and radial velocities (Sicilia-Aguilar et al., 2015). Key diagnostics of these processes are accessible in the optical bands with high resolution spectroscopy:

- Decomposition of emission line profiles showing structure within the accretion column.
- Detection of companions from radial velocity signatures.
- Details of the jet/ISM interaction.
- Details on mass loss, momentum transport.
- Substructure in the forbidden line HVC.
- Details on the narrow component of the forbidden line LVC, including turbulence information in the disk wind.

The present state of the art is exemplified by optical echelle spectrographs such as HIRES on the 10-m Keck telescope [300-1000 nm, R up to 85K] and UVES on the 8.2-meter VLT [300-1100 nm, up to R 80K on blue and 110K on red]. On the right side of Figure 2 is shown example Keck/HIRES spectra at R ∼48K probing the disk wind and outflow launching environments. An instrument such as TMT/HIRES or GMT/G-CLEF would enable similar observations at a factor of nine increase in sensitivity, giving access to the finest details and temporal variability of the gas flow in these regions.

References

Banzatti, A., Pascucci, I., Edwards, S., et al. 2019, ApJ, 870, 76

Davis, C. J., Hodapp, K. W., & Desroches, L. 2001, A&A, 377, 285

Djupvik, A. A., Liimets, T., Zinnecker, H., et al. 2016, A&A, 587, A75

Fang, M., Pascucci, I., Edwards, S., et al. 2018, ApJ, 868, 28

Flaherty, K. M., Hughes, A. M., Teague, R., et al. 2018, ApJ, 856, 117

Frank, A., Ray, T. P., Cabrit, S., et al. 2014, in Protostars and Planets VI, ed. H. Beuther, R. S. Klessen, C. P. Dullemond, & T. Henning, 451

Haworth, T. J., Ilee, J. D., Forgan, D. H., et al. 2016, Publications of the Astronomical Society of Australia, 33, e053

Najita, J. R., & Bergin, E. A. 2018, ApJ, 864, 168

Pascucci, I., Sterzik, M., Alexander, R. D., et al. 2011, ApJ, 736, 13

Riaz, B., & Whelan, E. T. 2015, ApJ, 815, L31

Schneider, P. C., Eislöffel, J., Güdel, M., et al. 2014, in European Physical Journal Web of Conferences, Vol. 64, 08007

Sicilia-Aguilar, A., Fang, M., Roccatagliata, V., et al. 2015, A&A, 580, A82

Sicilia-Aguilar, A., Banzatti, A., Carmona, A., et al. 2016, Publications of the Astronomical Society of Australia, 33, e059

Simon, M. N., Pascucci, I., Edwards, S., et al. 2016, ApJ, 831, 169

Suriano, S. S., Li, Z.-Y., Krasnopolsky, R., Suzuki, T. K., & Shang, H. 2019, MNRAS, 484, 107

Teague, R., Guilloteau, S., Semenov, D., et al. 2016, A&A, 592, A49