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Reflections on the discovery space for a large ultraviolet-visible telescope: inputs from the European-led EUVO exercise

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1 **Abstract.** The solutions to a number of astrophysical problems require access to the ultraviolet, optical, and infrared from space-based facilities, with capabilities beyond those available with Hubble Space Telescope
2 or JWST. A large ultraviolet-optical-infrared telescope will need to have a large collecting area and milliarcsecond angular resolution capabilities plus highly efficient instruments, providing a revolutionary enhancement in capability. During 2013, the European astronomical community was involved in an exercise to outline the big science that could be achieved with such a facility; the proposal was called EUVO (as per European Ultraviolet-Visible Observatory). Inspired by that work, we describe a proposal on future science and instrumentation to be carried out with a 10-m class telescope. [DOI: 10.1117/1.JATIS.2.4.XXXXXX]

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1 Introduction

In March 2013, the European Space Agency (ESA) announced an open call for white papers and science drivers for the Cosmic Vision program, the scientific space program for the 2015 to 2025 decade. The call was very successful and 32 white papers were submitted providing new ideas and technologies for forthcoming ESA large missions (see the details in Ref. 1). Among them, there was the proposal to build a large ultraviolet-visible observatory (EUVO) to address unexplored areas of the Cosmic Vision program.

The white paper focused on the ultraviolet (UV) range because the UV is an essential spectral interval for all fields of astrophysical research; imaging and spectral coverage at UV wavelengths provide access to diagnostic indicators for diffuse plasmas in space, from planetary atmospheres to elusive gas in the intergalactic medium (IGM). Linking visible and UV spectral features covers the widest possible range of species and a vast range of temperatures that cover most astrophysical processes. Moreover, UV observations are essential for studying the processes outside strict thermal equilibrium that produce conditions favorable to complex chemistry; the production pathway for the large molecules that are the basis of living structures. In addition, UV-visible instrumentation provides the best possible angular resolution for normal incidence optics, since diffraction-limited angular resolution is proportional to the radiation wavelength.

The consortium behind EUVO foresaw this proposal as the way of addressing key issues in the Cosmic Vision program, such as the investigation of planets and life, the chemical evolution of the universe, or the interaction between galaxies and IGM, that demand a large UV facility to observe diffuse matter in space. In a subsequent article,[2] a list of requirements was produced for such a facility.

This paper is not intended to provide a detailed listing of the many reasons to have a large UV facility in space; there are already reports, proposals, and online articles available: just browse the NASA site or the collection of conference proceedings edited by the Network of Ultraviolet Astronomy. Instead, we assume that a facility with a collecting power similar to a 10-m telescope {∼50 times the effective area [the radiometric efficiency of a new 10-m class facility is measured in terms of the collecting surface (a factor 17.4 increase with respect to Hubble)] and in the improvement of the optics and coatings, as well as in the increase of the detector's quantum efficiency (QE) (see Ref. 2 for more details). Cooled CCD[3] may provide QEs larger than 30% at wavelengths larger than 1300 Å.] of 3
Hubble} and an angular resolution 1 to 10 mas is available, as inspired by the EUVO consortium work. We analyze its impact in three key areas of astrophysical research: the formation and evolution of protoplanetary disks, the physics of stellar dynamos and stellar winds, and the evolution of exoplanetary systems, which are all related to exoplanetary research, a key theme for astronomical research in the next decades. Different instrumental capabilities are required for each topic: milliarcsecond angular resolution imaging (MASI), spectropolarimetry, and high-resolution spectroscopy in the 900- to 1700-Å spectral

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range, respectively. We devote a section to each topic and add a short summary at the end of the paper.

2 From Disks to Planets: Tracking the Evolution of Protoplanetary Disks

The formation and evolution of planetary systems are governed by gravity, magnetic fields, and the hard radiation (x-ray and UV) from the star. Understanding the formation of exoplanets, including the terrestrial ones, and of their atmospheres calls for a deep study of the life cycle of protoplanetary disks (PPDs).

Accretion disks are very common structures in the universe; they are the means for nature to channel mass accretion when the intrinsic angular momentum of the infalling gas is high. They work on a poorly known mechanism that transports angular momentum from the large scale into the viscous/micro scale where the angular momentum excess is released as heat.[4] In the most widely used approach, the so-called α-disk, the disk is treated as a set of nested rings with matter orbiting as per Kepler's laws; for the matter from the outer disk to reach the stellar surface, viscosity and shear between adjacent rings need to be invoked. The excess angular momentum is supposed to be transported to the eddy scale producing the subsequent heating of the disk. The spectral energy distribution predicted by this simple model fits well the integrated radiative output from PPDs disks[5] in spite of the uncertainties about its physical foundations and operation. Since 1991, magneto rotational instability (MRI)[6,7] has been thought to play a key role in enabling the radial transport of mass. However, to operate, MRI requires disk ionization fractions that are not met by the gas in some areas of PPDs;[8] for solar-like stars, this MRI dead zone is located in the planet formation zone[9] (at radii from 1 to 10 AU). Many ideas have been advanced to solve this problem in the context of PPD evolution. To mention but a few: the onset of turbulent mixing in the PPDs dead zone,[10] the action of gravitational instabilities and density waves as additional mechanisms for angular transport,[11] or a more realistic evaluation of the energy budget irradiating the disk, including the outflow contribution. However, only direct imaging of the inner 20 AUs of PPDs can provide the data to determine the sources of radiation accurately, to measure the radiation field reaching the surface of PPDs, map the gravitational/density waves acting on the disk, and study the variation of the disk temperature from the mid plane (at infrared wavelengths) to the atmosphere (at UV wavelengths) for radii in the 1- to 100-AU range. MASI is required to rigorously address the physics of PPDs since all spectroscopic means rely on the Keplerian rotation of the disk and derive the disk structure based on the Doppler shifting/broadening of the relevant spectral tracers.

MASI is also required to study PPD evolution and planet formation. The lifetime, spatial distribution, and composition of the gas and dust of young (age < 30 Myr) disks are important properties for understanding the formation and evolution of extrasolar planetary systems. Disk gas regulates planetary migration[12–14] and the migration timescale is sensitive to the specifics of the disk surface density distribution and dissipation timescale.[15] Moreover, the formation of giant planet cores and their accretion of gaseous envelopes occur on timescales similar to the lifetimes of the disks around premain sequence (PMS) stars (1 to 10 Myr).

UV radiation from the stellar magnetosphere and the jet is very efficient at etching the disk surface through photoevaporative flows[16] and determines the lifetime of the gaseous component of disks. The dust disk clearing timescale is expected to be 2 to 4 Myr.[17] However, recent results indicate that inner molecular disks can persist to ages ~10 Myr in Classical T Tauri stars.[18,19] Both the intensity and the spectral distribution of the far UV (900 to 2000 Å) radiation field have a strong influence on the chemical abundances of the disk and control the chemistry of the external layers.[20,21]

In debris disks, observation of volatiles released by dust, planetesimals, and comets provides an extremely powerful tool for determining the relative abundances of the vaporizing species and studying the photochemical and physical processes acting in the inner parts of the disks.[22–24]

The main laboratories of star formation are within a radius of ~150 pc radius around the Sun.[25,26] This ring marks the molecular walls of the Local Bubble in the ISM and forms part of a local 4
kinematic and physical structure in the galaxy known as the Gould's Belt. Thus, this distance defines the target angular resolution for disk studies: 7 mas to resolve 1 AU scales or 0.7 mas to resolve the boundary between the star and the disk. Currently, the only way to achieve such a high resolution is by means of interferometry at infrared wavelengths. Typical ground-based facilities have baselines of about 100 m and probe wavelengths of 1 to 13 μm, providing angular resolutions of 2 to 10 mas or 0.25 to 1.25 AU. As shown in Fig. 1, ground-based radio interferometry traces the large-scale structure of the disk but not the innermost region where the gravitational field is stronger and the transport mechanism in PPDs can be efficiently tested. MASI is fundamental to cover this area of the discovery space, not only for disks studies but also for understanding the formation of jets and collimated outflows during PMS evolution (see Fig. 1). Moreover, jets and the disk-star boundary layer radiate at UV-optical wavelengths. An additional advantage of MASI from a space-based facility such as large ultraviolet-optical-infrared (LUVOIR) is the field of view, which is not limited in the manner of interferometric observations.

2.1 *Connection Between Protoplanetary Disks and Bipolar Outflows*

Though bipolar outflows are the first signature of PPDs and star formation, no theory anticipated them prior to the discovery of the outflow from L1551.[29] The collimation and mechanical power of outflows decrease as stars approach the main sequence (MS) and PPDs evolve into debris disks.[30,31] The tracers of the outflows depend on the degree of evolution of the parent source. Flows from very young sources (10^4- to 10^5-years old) often contain molecules such as H_2, CO, and SiO. Later on, they tend to be dominated by HI and low-ionization metals that are observed as prominent large-scale jets detected at optical wavelengths ([S II], [N II], or Hα lines).[26] Mass-loss rates decline from $\sim 10^{-6}$ $M_\odot$ year^{-1} in the youngest sources to $\sim 10^{-10}$ $M_\odot$ year^{-1} before being switched off. Typically, the mass-loss rate is ~10% of the PPD accretion rate and the velocity is about a few hundred km s^{-1}.

The high kinetic energy of the outflow requires an efficient launching mechanism that acts from the very early phases of PPD evolution[32] (10^{3-4} yr). As protostars grow, material in the disk rotates faster while the effective gravity on the disk surface remains low; these conditions are favorable for the development of centrifugally driven outflows provided the disk surface is magnetized and threaded by open field lines. In the most basic approach, disk winds extend the nested rings set up from the α-disks into a nested Russian-doll scheme, where the large-scale bipolar outflow is perceived as a set of bipolar plasma

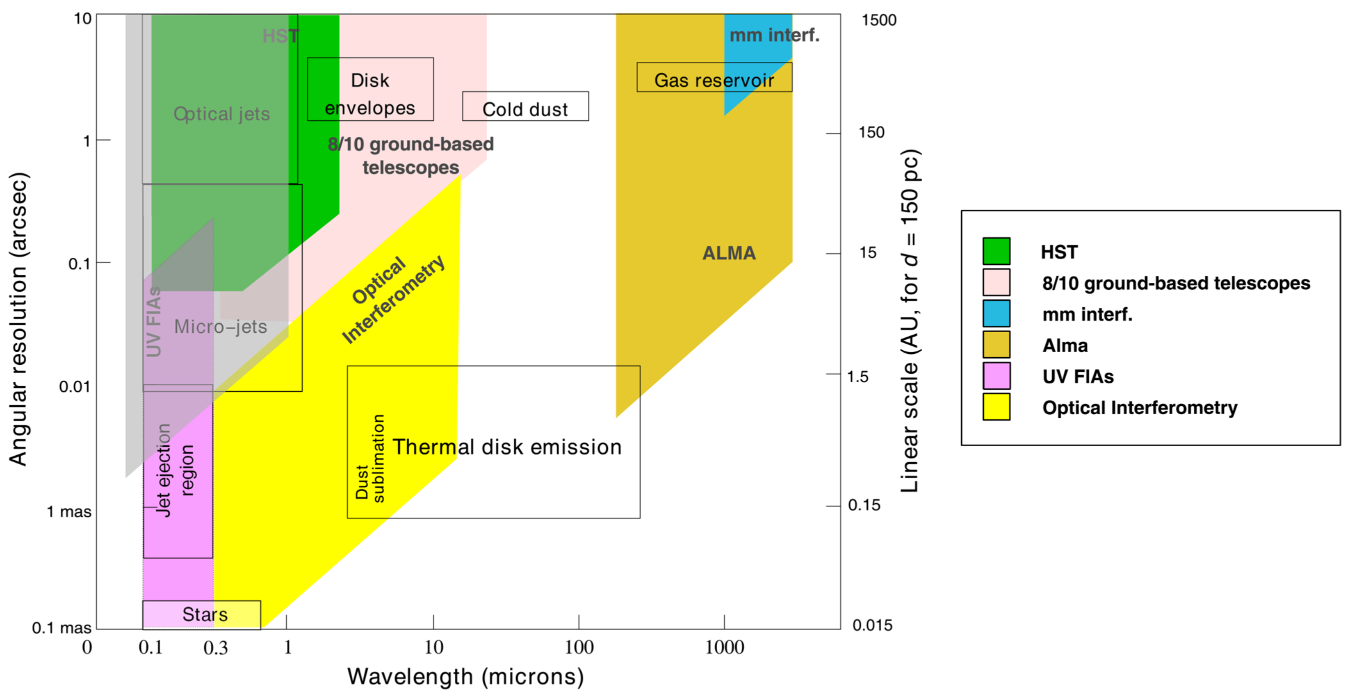

Fig. 1 Angular resolution versus wavelength diagram for current and foreseen facilities. The plot has been adopted from Ref. 27 and shows the discovery space for various astronomical facilities. The range to be covered by LUVOIR is shaded in gray. Areas of special interest for the main science topics in PPDs evolution and jet physics are indicated. The MASI capabilities of Fresnel interferometer arrays[28] are shown for comparison.

5 sheets anchored to each ring.[33] These centrifugally driven MHD disk winds (CDMW) are thought to play a key role in accretion by carrying out a fraction of the angular momentum excess linking accretion with outflow as otherwise observed. Bipolar outflows are predicted to rotate[32,34] and possible observational evidence for rotation has been suggested from the UV observation of the jet.[35] However, to test the theoretical framework, high angular resolution observations are required to resolve the CDMWs' launching zone[34,35] (<2 AU). As the jet radiates in the UV intercombination lines,[36,37] they can be used to probe the base of the jet and to study the jet collimation and rotation since with LUVOIR the best possible spatial resolution will be achieved at UV wavelengths.

High-velocity knots are observed in protostellar jets[38] and cannot be easily accommodated within the CDMW theory. They are believed to be generated at the interface between the stellar magnetosphere and the disk magnetic field, in a sheared boundary layer[39,40] between the star and the inner border of the PPD. Mass in-fall onto the star is regulated through this interaction,[39,41] which transforms a fraction of the angular momentum excess in the inner border of the PPD into magnetic field amplification that self-regulates through quiescent periods of field building up and eruptions when the energy excess is released. The magnetic pressure from the toroidal field pushes the magnetic field lines outward from the disk rotation axis, inflating and opening them into a butterfly-like pattern and producing a current layer between the star- and disk-dominated regions,[40–42] as outlined in Fig. 2. Magnetic field dissipation in the current layer also produces high-energy radiation (x-rays, EUV, and FUV radiation) and particles that contribute 6
to the ionization of the inner disk, where terrestrial planets form[9,12,13–15] (see Fig. 2).

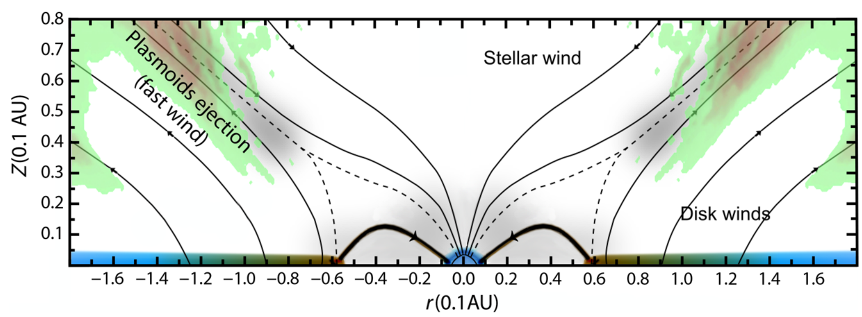

Fig. 2 Sketch of the accretion engine. The star acts as a magnetic rotor that interacts with the plasma orbiting around it in Keplerian orbits. The results of numerical simulations on the interaction between the stellar magnetosphere and the disk are shown;[42] they are color coded from light green to brown and represent the emissivity of the C III line at 191 nm. The magnetic configuration is outlined as well as the reconnection layer where magnetic bubbles are thought to be generated.

Also, the star-disk interaction distorts and powers the stellar magnetosphere leading to the formation of structures extending several stellar radii[41,42] that radiate strongly in the UV; typically a T Tauri star is about 50 times UV brighter than its MS analog.[43,44] MASI with LUVOIR will provide (in the UV) the best possible angular resolution; for a conservative angular resolution, based solely on the telescope diffraction limit at 1215 Å (the Lyman α wavelength), physical scales of 0.05 AU ($11R_\odot$) will be resolved in the nearest T Tauri stars such as AB Dor.

Many uncertainties remain due to the lack of observations to constrain the modelling. Very important questions still open are: How does the accretion flow proceed from the disk to the star? Is there any preferred accretion geometry, for instance funnel flows? What is the temperature distribution emerging from the accretion shock produced when matter shocks with the stellar atmosphere? What role do disk instabilities play in the whole accretion/outflow process? What are the dominant processes involved in wind acceleration? How does this mechanism work, if it does, when radiation pressure becomes significant as for Herbig Ae/Be stars? What are the relevant time-scales for mass ejection? How does the high-energy environment affect the chemical properties of the disk and planetary assembly? How do the stellar magnetospheres evolve? What is the role of binarity and planet formation in disk evolution? MASI at UVOIR wavelengths is needed to address these questions.

3 Stellar Magnetic Fields and Their Impact on Accretion and Mass-Loss Rates During Stellar Evolution

Magnetic fields pervade the galaxy; they are coupled to the gas/dust component and transmitted from the highly ionized (strongly coupled) components of the ISM into the molecular clouds. Hydromagnetic turbulence sustains the clouds against gravitational collapse and it is transported into the protostellar cores that lead to the formation of the stars. Fossil fields (100 G to a few kG) are observed in the radiative envelopes of hot stars, usually dominated by oblique dipoles.[45] Such fields may contain the imprint of subtle magneto-hydrodynamic processes occurring during the early phases of star formation, before the star is visible. Moreover, they have important consequences for later formation phases, especially in their role as intermediaries in accretion and mass-loss processes. During MS and post-MS evolution, fossil magnetic fields have been shown to couple strongly to stellar winds, enhancing the shedding of rotational angular momentum through magnetic braking.[46] Simultaneously, the presence of the field impedes mass loss, redirecting outflowing wind back toward the stellar surface. As rotation and mass loss are key determinants of the evolution of hot stars, magnetic fields potentially have an enormous impact.

As opposed to hot stars, cool stars (i.e., spectral types later than mid-F), as well as brown dwarfs, possess an outer convective envelope, where any fossil field would be rapidly dissipated. The magnetic fields observed at the photospheric level on these objects (between 1 G on average and a few thousand G locally) are, therefore, thought to be generated and sustained by dynamo action, as was first observationally verified for the Sun 60 years ago.[47] As a consequence, the magnetic fields of cool stars are not frozen but are instead highly dynamic and exhibit variability on a very wide range of time-scales. The internal structure of the star, its rotation, and its accretion state can strongly influence the dynamo, and ultimately set the broad properties of the magnetic field. The dynamo-generated magnetic field, in turn, drives the mass loss and angular momentum loss through magnetized winds and coronal mass ejection processes. Therefore, a complex interplay exists between magnetic fields and the rotation of cool stars during their whole evolution.

Over the last decade, ground-based spectropolarimetric surveys in the visible domain (such as the Bcool project[48]) have revolutionized our knowledge of the magnetic fields of cool stars. We are now developing a global view of how the properties of cool stars' magnetic fields depend on stellar mass and rotation.[49] We also better understand how the transition from a partly to a fully convective internal structure at the lowest stellar masses impacts the dynamo.[50] Last, but not least, we are beginning to describe the evolution of the magnetic field of solar-type stars along their MS evolution.[51]

The results of spectropolarimetric studies constitute key observational constraints for magnetic dynamo and fossil theories and stellar evolution models, as well as for the understanding of stellar activity and its impact on planets. However, they only constitute initial steps. A 10-m class space telescope equipped with instrumentation for simultaneous UV and visible high-resolution spectropolarimetry will allow users, for the first time, to fully characterize magnetic fields of a large sample of stars on time-scales ranging from minutes to years and their relation with activity indices from the UV to the red end of the visible domain. Such an instrument will provide a unique opportunity to investigate the full dynamic nature of stellar magnetism. These observations will also be pivotal for the study of the activity of the Sun. While we model solar activity using observations from x-rays to the radio range, including spectropolarimetry to deduce the magnetic field, these multiwavelength studies are limited to a single star, the Sun. Extending such observables to solar-like stars will provide a much larger set of observations to challenge and test activity models. In particular, the relation between the magnetic field and the emission properties deduced over a wide wavelength domain for a range of different stellar activities will provide crucial data to better understand our own star. This will contribute an important piece to the puzzle of how the dynamo works in the Sun and created the cycle of activity that has a direct impact on life on Earth. The ARAGO mission is intended for this purpose.[52]

Spectropolarimetric studies will benefit extraordinarily from the use of large collecting surfaces such as that intended for LUVOIR. The analysis of the polarized radiation requires the light beam to be split into two (or more) polarization states and optical elements such as polarizers are rather inefficient in the UV.[53] The optical design of the UV-branch of the spectropolarimeter proposed for the ARAGO mission[54] has been optimized in terms of image quality (to simultaneously obtain the spectrum in two polarization states) and simultaneous wavelength coverage; it covers the 1150- to 3200-Å range in a single spectrum with dispersion 25,000.

4 Chemical Composition of Exoplanets: Evolved Planetary Systems

Practically, all known planet host stars, including the Sun, will evolve into white dwarfs, and many of their planets will survive.[55,56] Observational evidence for such evolved planetary systems includes the detection of trace metals in the white dwarf photospheres[57] and infrared and optical emission from circumstellar debris disks.[58–60] The generally accepted model explaining these observations is the tidal disruption of asteroids, minor

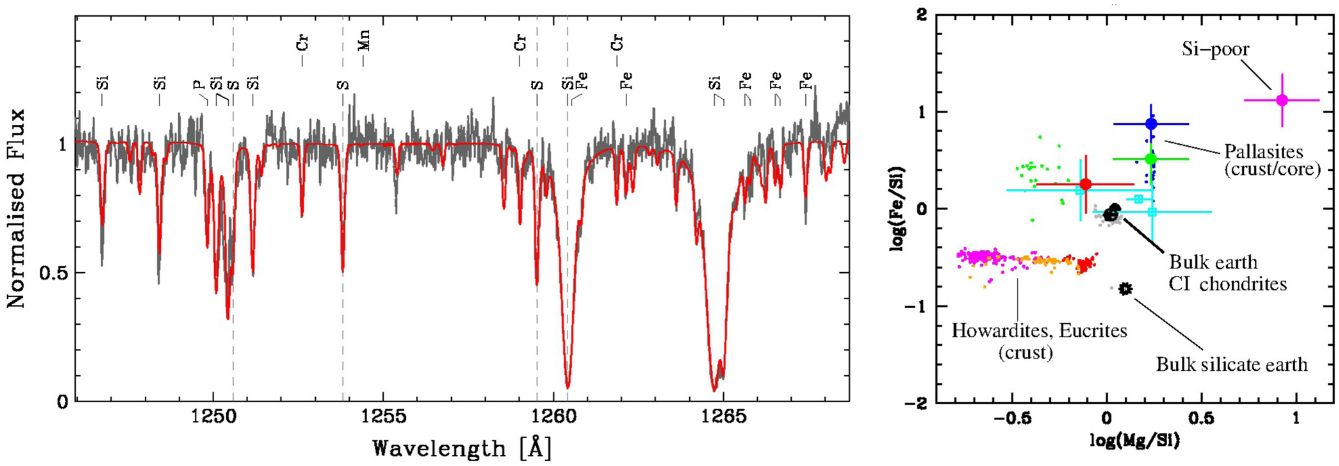

Fig. 3 Planetary debris are detected in far-UV spectroscopy of white dwarfs (left, HST/COS), providing bulk-abundances for exoplanetary bodies with masses of $\sim 10^{20}$ to 10^{25} g. About 15 systems studied so far are all "rocky" but show a large variety in their detailed composition (right: large dots with error bars are extrasolar planetesimals and small dots are solar system meteorites).

planets, or planets,[61] perturbed into star-crossing orbits by dynamical interactions with planets. Spectroscopic surveys now unambiguously demonstrate that 25% to 50% of white dwarfs host evolved planetary systems.[62]

Measuring the photospheric abundances of debris-polluted white dwarfs provides an unrivaled window into the bulk composition of exoplanetary material[63] for planetary bodies with masses of 10^{20} to 10^{25} g, i.e., ranging from several 10-km-sized asteroids to nearly the mass of Pluto.

The UV wavelength range is fundamental for this work, as it contains strong transitions of the rock-forming elements (Si, Fe, Mg, and O), refractory lithophiles (Ca, Al, and Ti), and in particular, volatile elements (C, N, P, and S) that trace the formation region of the planetary material relative to the snow line. The diagnostic potential of extrasolar cosmochemistry using white dwarfs is shown by Hubble Space Telescope (HST) observations, corroborating the rocky, volatile-depleted nature of the planetesimals,[64] and detecting a variety in bulk compositions similar to, if not exceeding, that seen among solar-system bodies. Also, water-rich planetesimals have been discovered,[65] which provide the potential for delivering water to planets in the habitable zone (see Fig. 3).

The measured planetary debris abundances provide important input into our understanding of planet formation. Of particular importance for the properties of planetary systems are the C/O and Mg/Si ratios. C/O ratios >0.8 would result in a radically different setup from the solar system, with O-chemistry replaced by C-chemistry, which is discussed abundantly in the literature (see, e.g., Ref. 66). The Mg/Si ratio determines the exact composition of silicates, which in turn has implications for planetary processes such as plate tectonics. Furthermore, the relative abundances of Fe and siderophiles (Cr, Mn, S, and Ni), and of refractory lithophiles (Al, Ca, and Ti) provide insight into the core and crust formation, respectively.[67] As opposed to indirect measurements, such as abundance studies of planet host stars, far-UV spectroscopy of debris-polluted white dwarfs provides a "direct measure" of those ratios.

However, global insight into the chemistry of planetary systems will only be possible from the detailed photospheric abundance studies of a substantial number of white dwarfs. The current roster of planetary debris abundance studies[66] with at least five detected elements stands at ∼15.

The known sample of evolved planetary systems is growing rapidly. A 10-m class UV observatory equipped with a high resolution (20,000 to 50,000) spectrograph in the 950- to 1800-Å range will make feasible a large-scale statistical study of the bulk abundances of exoplanetary systems; several hundreds of debris polluted white dwarfs could be observed.

5 Summary

The HST and its suite of instruments have inevitably set the standard for UV and visible astronomy from space. Conceived as a general-purpose observatory, it has been able to study a wide variety of scientific goals by providing diffraction-limited imaging and spectroscopy from low to high resolution across a wavelength range from the far UV to the near-infrared. In its current configuration, the telescope has an efficient capability that continues to deliver exciting new discoveries. However, the exploration of exoplanetary systems will require a factor of 30 to 50 increase in effective area with respect to HST and reach the best possible angular (<10 mas). Such a capability will also produce a revolution in the study of astrophysical disks and jets. Furthermore, the implementation of a few carefully selected instruments will allow collection of the data needed to understand the physics behind planet formation, planetary atmospheric stability and evolution, the interaction between the components of planetary systems and the census of the metallic compounds.

Our proposal for the baseline instrumentation (in the UV-optical range) of such facility is:

- To observe the inner 10 AUs of the PPDs, a "high angular resolution," high-quality "imaging instrument" is required. The best possible angular resolution to be reached with a 10-m circular aperture telescope is 3 mas at 1200 Å; should this optimal performance be reached, the interface between the stellar magnetosphere and the PPDs would be resolved in sources like TW Hya (an accreting T Tauri star at 40 pc). Angular resolutions better (<) than 10 mas and at UV wavelengths will provide crucial data about the inner structure of PPDs and the collimation of the protostellar jets.

- To study the kinematics of the jets and the impact of binarity in the evolution of the inner 10 AUs of PPDs, an instrument to carry out "integral field spectroscopy" is required. Dispersions of ∼20,000 will be needed.
- To measure the strength and topology of the stellar magnetic fields during PMS evolution, a spectropolarimeter with $R = 20{,}000$ to 100,000 in the 1000- to 7000-Å spectral range is required
- To determine the composition of PPDs (either molecular or atomic) and their evolution, a spectrograph is required that, at least, covers the 900- to 2000-Å spectral range with low-/medium- to high-resolution echelle capability, $R = 20{,}000$ to 100,000.

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References

8 1. http://sci.esa.int/cosmic-vision/52030-white-papers-submitted-in-response-
9 to-esas-call-for-science-themes-for-the-l2-and-l3-missions/\#.
2. A. I. Gómez de Castro et al., "Building galaxies, stars, planets and the ingredients for life between the stars. The science behind the European ultraviolet-visible observatory," *Astrophys. Space Sci.* **354**, 229–246 (2014).
3. A. Shugarov et al., "UV detectors for spectrographs of WSO-UV project," *Astrophys. Space Sci.* **354**, 169–175 (2014).
10 4. N. I. Shakura and R. A. Sunyaev, "Black holes in binary systems. Observational appearance," *Astron. Astrophys.* **24**, 337 (1973).
5. F. C. Adams, C. J. Lada, and F. H. Shu, "Spectral evolution of young stellar objects," *Astrophys. J.* **312**, 788 (1987).
6. S. A. Balbus and J. E. Hawley, "A powerful local shear instability in weakly magnetized disks. I-Linear analysis. II-Nonlinear evolution," *Astrophys. J.* **376**, 214 (1991).
7. J. M. Stone, "Protostellar jets in context," in *Astrophysics and Space Science Proc. Series*, K. Tsinganos, T. Ray, and M. Stute, Eds., Springer, Berlin (2009).
8. C. F. Gamie, "Layered accretion in T Tauri disks," *Astrophys. J.* **457**, 355 (1996).
9. N. Dzyurkevich et al., "Magnetized accretion and dead zones in protostellar disks," *Astrophys. J.* **765**, 114 (2013).
10. J. Igea and A. E. Glassgold, "X-ray ionization of the disks of young stellar objects," *Astrophys. J.*, **518**, 848–858 (1999).
11. W. K. M. Rice, G. Lodato, and P. J. Armitage, "Investigating fragmentation conditions in self-gravitating accretion discs," *Mon. Not. R. Astron. Soc.* **364**, L56 (2005).
12. W. R. Ward, "Survival of planetary systems," *Astrophys. J. Lett.* **482**, L211 (1997).
13. P. J. Armitage et al., "Predictions for the frequency and orbital radii of massive extrasolar planets," *Mon. Not. R. Astron. Soc.* **334**, 248–256 (2002).
14. D. E. Trilling et al., "Orbital migration and the frequency of giant planet formation," *Astron. Astrophys.* **394**, 241–251 (2002).
15. P. J. Armitage, "Massive planet migration: theoretical predictions and comparison with observations," *Astrophys. J.* **665**, 1381–1390 (2007).
16. R. Alexander et al., *Protostars and Planets VI*, H. Beuther et al., Eds., p. 475, University of Arizona Press, Tucson (2014).
17. J. Hernandez et al., "Spitzer observations of the orion OB1 association: disk census in the low-mass stars," *Astrophys. J.* **671**, 1784–1799 (2007).
18. K. France et al., "A Hubble space telescope survey of H_2 emission in the circumstellar environments of young stars," *Astrophys. J.* **756**, 171 (2012).
19. C. Salyk et al., "High-resolution 5 μm spectroscopy of transitional disks," *Astrophys. J.* **699**, 330–347 (2009).
20. G.-J. van Zadelhoff, Y. Aikawa, and M.R. Hogerheijde, "Axi-symmetric models of ultraviolet radiative transfer with applications to circumstellar disk chemistry," *Astron. Astrophys.* **397**, 789–802 (2003).
21. E. Bergin et al., *Protostars and Planets, V*, B. Reipurth, D. Jewitt, and K. Keil, Eds., p. 751, University of Arizona Press, Tucson (2007).
22. A. Roberge et al., "Stabilization of the disk around β Pictoris by extremely carbon-rich gas," *Nature* **441**, 724–726 (2006).
23. A. Vidal-Madjar, A. L. des Etangs, and R. Ferlet, "β Pictoris, a young planetary system? A review," *Planet. Space Sci.* **46**, 629–648 (1998).
24. A. L. des Etangs et al., "FUSE observations of H_2 around the Herbig AeBe stars HD 100546 and HD 163296," *Astron. Astrophys.* **407**, 935–939 (2003).
25. A. I. Gómez de Castro, "The formation of planetary disks and winds: an ultraviolet view," *Astrophys. Space Sci.* **320**, 97–106 (2009).
26. A. I. Gómez de Castro, *Planets, Stars and Stellar Systems*, T. D. Oswalt and M. A. Barstow, Eds., Vol. **4**, p. 279, Springer Science+Business Media, Dordrecht (2013).
27. A. I. Gómez de Castro, "The Fresnel space imager as a disk evolution watcher," *Exp. Astron.* **30**, 205–216 (2011).
28. L. Koechlin et al., "The Fresnel interferometric imager," *Exp. Astron.* **23**, 379–402 (2009).
29. R. L. Snell, R. B. Loren, and R. L. Plambeck, "Observations of CO in L1551-Evidence for stellar wind driven shocks," *Astrophys. J.* **239**, L17 (1980).
30. H. G. Arce and A. I. Sargent, "The evolution of outflow-envelope interactions in low-mass protostars," *Astrophys. J.* **646**, 1070–1085 (2006).
31. P. Andre et al., "Discovery of a remarkable bipolar flow and exciting source in the Rho Ophiuchi cloud core," *Astron. Astrophys.* **236**, 80 (1990).
32. G. Pelletier, R. E. Pudriz, and A. I. Gómez de Castro, *The Physics of Star Formation and Early Stellar Evolution*, NATO Advanced Science Institutes (ASI) Series C, C. J. Lada and N. D. Kylafis, Eds., Vol. **342**, p. 539, Kluwer, Dordrecht (1991).
33. C. Ferro-Fontán and A. I. Gómez de Castro, "On the source of dense outflows from T Tauri stars—I. Photoionization of cool MHD disc winds," *Mon. Not. R. Astron. Soc.* **342**, 427–438 (2003).
34. A. I. Gómez de Castro and R. E. Pudritz, "The origin of forbidden line emission from young stellar objects," *Astrophys. J.* **409**, 748 (1993).
35. D. Coffey et al., "Jet rotation investigated in the near-ultraviolet with the hubble space telescope imaging spectrograph," *Astrophys. J.* **749**, 139 (2012).
36. A. I. Gómez de Castro and E. Verdugo, "New constraints on protostellar jet collimation from high-density gas UV tracers," *Astrophys. J.* **548** 976–989 (2001).
37. A. I. Gómez de Castro and E. Verdugo, "Hubble space telescope STIS spectrum of RW Aurigae A: evidence for an ionized beltlike structure and mass ejection in timescales of a few hours," *Astrophys. J.* **597**, 443–454 (2003).
38. J. Eisloeffel and R. Mundt, "Proper motion measurements and high resolution imaging of the HH 46/47 outflow," *Astron. Astrophys.* **284**, 530 (1994).
39. F. Goodson et al., "Time-dependent accretion by magnetic young stellar objects as a launching mechanism for stellar jets," *Astrophys. J.* **489**, 199–209 (1997).
40. B. Von Rekowski and A. Brandenburg, "Stellar dynamo driven wind braking versus disc coupling," *Astron. Nachr.* **327**, 53–71 (2006).
41. M. M. Romanova et al., "MRI-driven accretion on to magnetized stars: global 3D MHD simulations of magnetospheric and boundary layer regimes," *Mon. Not. R. Astron. Soc.* **421**, 63 (2012).
42. A. I. Gómez de Castro and B. Von Rekowski, "On the source of dense outflows from T Tauri stars-III. Winds driven from the star-disc shear layer," *Mon. Not. R. Astron. Soc.* **411**, 849–858 (2011).
43. C. M. Johns-Krull, J. A. Valenti, and C. Koresko, "Measuring the magnetic field on the classical T Tauri star BP Tauri," *Astrophys. J.* **516**, 900–915 (1999).
44. A. I. Gómez de Castro and P. Marcos-Arenal, *Astrophys. J.* **516**, 11
900–915 (1999).

45. E. Alecian et al., "A high-resolution spectropolarimetric survey of Herbig Ae/Be stars-I. Observations and measurements," *Mon. Not. R. Astron. Soc.* **429**, 1001–1026 (2013).
46. R. H. D. Townsend et al., "Discovery of rotational braking in the magnetic helium-strong star sigma Orionis E," *Astrophys. J. Lett.* **714**, L318 (2010).
47. E. N. Parker, "Hydromagnetic dynamo models," *Astrophys. J.* **122**, 293 (1955).
48. S. C. Marsden et al., "A Bcool magnetic snapshot survey of solar-type stars," *Mon. Not. R. Astron. Soc.* **444**, 3517–3536 (2014).
49. J.-F. Donati and J. Landstreet, "Magnetic fields of nondegenerate stars," *Ann. Rev. Astron. Astrophys.* **47**, 333–370 (2009).
50. J. Morin et al., "Large-scale magnetic topologies of mid M dwarfs," *Mon. Not. R. Astron. Soc.* **390**, 567–581 (2008).
51. A. A. Vidotto et al., "Stellar magnetism: empirical trends with age and rotation," *Mon. Not. R. Astron. Soc.* **441**, 2361–2374 (2014).
52. M. Pertenais et al., "Static spectropolarimeter concept adapted to space conditions and wide spectrum constraints," *Appl. Opt.* **54**, 7377 (2015).
53. C. Neiner et al., "UVMag: stellar formation, evolution, structure and environment with space UV and visible spectropolarimetry," *Astrophys. Space Sci.* **354**, 215–227 (2014)

12 54. A. I. Gómez de Castro et al., "Optical design for the ARAGO ultraviolet spectrograph," ARAGO-TN-UCM-003 (2016).

55. E. Villaver et al., "Hot jupiters and cool stars," *Astrophys. J.* **794**, 3 (2014).
56. D. Veras et al., "Simulations of two-planet systems through all phases of stellar evolution: implications for the instability boundary and white dwarf pollution," *Mon. Not. R. Astron. Soc.* **431**, 1686–1708 (2013).
57. D. Koester et al., *Astron. Astrophys.* **320**, L57 (1997).
58. B. Zuckerman and E. E. Becklin, "Companions to white dwarfs-very low-mass stars and the brown dwarf candidate GD 165B," *Astrophys. J.* **386**, 260 (1992).
59. B. T. Gänsicke et al., "A gaseous metal disk around a white dwarf," *Science* **314**, 1908–1910 (2006).
60. J. Farihi et al., "Infrared signatures of disrupted minor planets at white dwarfs," *Astrophys. J.* **694**, 805–819 (2009).
61. D. Veras et al., "Formation of planetary debris discs around white dwarfs-I. Tidal disruption of an extremely eccentric asteroid," *Mon. Not. R. Astron. Soc.* **445**, 2244–2255 (2014).
62. D. Koester et al., "The frequency of planetary debris around young white dwarfs," *Astron. Astrophys.* **566**, A34 (2014).
63. B. Zuckerman et al., "The chemical composition of an extrasolar minor planet," *Astrophys. J.* **671**, 872–877 (2007).
64. M. Jura et al., "Two extrasolar asteroids with low volatile-element mass fractions," *Astrophys. J.* **750**, 69 (2012).
65. J. Farihi et al., "Evidence for water in the rocky debris of a disrupted extrasolar minor planet," *Science* **342**, 218–220 (2013).
66. J. Moriaty et al., "Chemistry in an evolving protoplanetary disk: effects on terrestrial planet composition," *Astrophys. J.* **787**, 81 (2014).
67. M. Jura and E. D. Young, "Extrasolar cosmochemistry," *Annu. Rev. Earth Planet. Sci.* **42**, 45–67 (2014).

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