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ISM SCIENCE WITH POLLUX

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Abstract. The far-UV wavelength range provides access to tracers of the interstellar medium (ISM) in potentially all phases (neutral/ionized, atomic/molecular, dense/diffuse, hot/warm/cold). The combination of high spatial resolution and sensitivity enabled by the LUVOIR telescope, together with the high spectral resolution and polarization capabilities enabled by the POLLUX instrument will open a new era of exquisite details for Milky Way ISM studies (e.g., molecular gas properties, molecule formation pathways, origin and distribution of phases...) and a dramatic improvement of the ISM properties in nearby galaxies (e.g., interplay between galaxy evolution and ISM properties, metallicity build-up, influence of the environment...).

Keywords: instrumentation: spectrographs, ISM: general, ISM: clouds, ISM: magnetic fields, galaxies: ISM, ultraviolet: ISM

1 Absorption measurements

1.1 Observational technique and ISM tracers

The far-ultraviolet (FUV) wavelength range provides a unique probe of the interstellar medium (ISM) by enabling the observation of absorption lines arising in ISM clouds either:

- within external galaxies toward a quasar line of sight,
- within an external galaxy toward individual FUV-bright sources (e.g., O stars) or unresolved clusters (e.g., OB associations, H II region...),
- within the Milky Way toward Galactic stars.

For extragalactic lines of sight, the ISM from the Milky Way and from low/intermediate/high-velocity clouds constitute a possible contamination. The FUV domain provides access to ISM tracers in various phases and ionization states:

- Neutral hydrogen Lyman series notably as a reference for chemical abundances and for the atomic-to-molecular gas transition. Remarkably low column densities can be reached, as low as $10^{13}\,\mathrm{cm}^{-2}$ (much lower than what is currently possible using H I 21 cm) that can probe infalling gas or filaments from the cosmic web toward specific lines of sight (e.g., Lehner et al. 2006).
- Deuterium (either atomic or as HD) as a constraint for Big Bang nucleosynthesis models (e.g., Wood et al. 2004).
- Molecular gas (H_2, CO, CH, CH^+... and the so-called "CO-dark" gas traced by fine-structure lines of C^0 and C^+) as a probe of molecular gas formation, of the relationship between molecular gas and star formation, and of the dissipation of turbulence (e.g., Valdivia et al. 2017).
- Ionized gas species as a probe of the warm ionized medium, of partially-ionized neutral gas (e.g., by extreme-UV or soft X-ray photoionization; Jenkins 2013), and of collisionally-excited hot gas (e.g., Wakker et al. 2003; Otte & Dixon 2006; Welsh & Lallement 2008).
- Neutral gas metallic species as a probe of the chemical enrichment, of the dust grain composition through depletion patterns, and of cooling pathways (e.g., Lebouteiller et al. 2009, 2013).

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1.2 The need for spectral resolution

Spectral resolution is essential in order to measure the intrinsic line width of individual lines ($\approx$ 2.5km s^{-1} for the cold/warm gas or $\approx$ 24km s^{-1} for the hot gas, corresponding to a resolution power of 10^{4-5}) and to examine the velocity profile. Local ISM studies have been able to benefit from high spectral resolution with Orfeus-SPAS II-IMAPS and HST/STIS, finding for instance that H_2 may form in post-shock zones through the H^- path in a partially-ionized gas (Jenkins & Peimbert 1997) or that dissipation of turbulence may play a role in the endothermic formation of CH^+ (Nehmé et al. 2008; Valdivia et al. 2017).

Spectral resolution is also essential to distinguish individual clouds along each line of sight, in particular toward extragalactic sources. With low spectral resolution observations of blended velocity components, the global properties derived from the detection of a single absorption feature may not correspond to a simple average property because of non-linear effects with column density and potentially hidden saturated components (e.g., Pettini & Lipman 1995).

1.3 The need for spatial resolution

Low spatial resolution has mostly been a problem for ISM observations in nearby galaxies where the lines of sight toward individual O and B stars cannot be distinguished because young massive stars are usually crowded in H II regions or simply the galaxy is too far away. For this reason, studies of the ISM toward individual lines of sight toward stars in external galaxies have been mostly limited to the Magellanic Clouds (e.g., Mallouris 2003) and bright giant H II regions in the local group (Lebouteiller 2005). High spectral resolution makes it possible to separate components along any given line of sight but FUSE and previous telescopes could only measure in nearby galaxies the integrated light from a collection of stars, resulting not only in a degraded spectral resolution but most importantly producing important biases due to non-linear effects (lines of sight toward stars with different brightness, intersecting clouds with different column densities, turbulent velocity...). A combination of high spatial resolution and spectral resolution enables the identification of ISM clouds in the 3D space and solves the biases in column density determination.

1.4 The need for polarization

The Planck telescope enabled the measurement of dust polarization, though at large spatial scales ($> 10'$) and integrated in any given direction. In contrast, the *gas* polarization is not only complementary but also potentially much more versatile, enabling measurements in different phases, at small spatial scales (either along a line of sight or in 3D), and in relatively weak fields. The linear polarization originating from angular momentum alignment of ground-state atoms (Yan & Lazarian 2012) can be produced from the anisotropy of the local interstellar radiation field or from a star in the vicinity (see example in Fig. 1). The ISM gas polarization in the FUV is completely unexplored but would help in understanding the actual distribution of the magnetic field and henceforth the role of the magnetic field in the ISM phase distribution, the role of magnetic pressure and turbulence, and the accretion of gas in star-forming filaments.

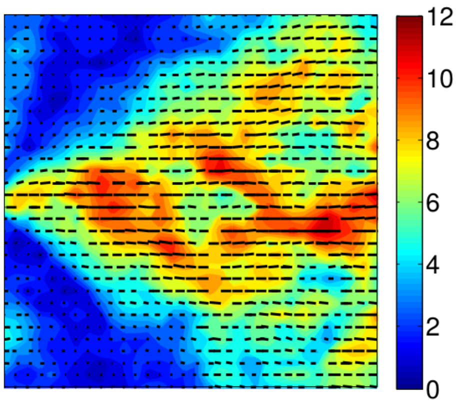

Fig. 1: Synthetic polarization (%) map of the simulated diffuse ISM (1 pc^2). Contour color: percentage of polarization in the S II 1250Å absorption line. Orientation of the bars: polarization direction. The mean magnetic field (3μG) is oriented along the x-axis. This figure shows that the direction of polarization correctly indicates the magnetic field direction and that the expected polarization is mostly above 5%, within POLLUX capabilities (Zhang et al. 2018).

Recent progress have also been made concerning observations and models of polarization of scattering Ly-α emission (usually the brightest line in young star-forming galaxies), which provides useful constraints on the kinematics and distribution of the scattering H I gas in high-z galaxies (Eide et al. 2018; Beck et al. 2016). LUVOIR and POLLUX would enable similar studies at low redshift.

2 Case study: ISM properties in nearby galaxies

While LUVOIR and POLLUX open a new era of in-depth knowledge of the Local ISM, the detailed physics that have been examined for the Local ISM so far will now become accessible in nearby galaxies. Hence it appears that an important prospect for LUVOIR is to explore the ISM properties in *different environments*, in particular for low metallicity conditions. From a technical point of view, LUVOIR is well adapted to the observation of individual lines of sight toward extragalactic sources in the nearby Universe (Sect. 1.3) while the POLLUX instrument (Muslimov et al. 2018; Bouret et al. 2018) provides the high spectral resolution and polarization capabilities needed for detailed ISM studies (Sects 1.2, 1.4).

2.1 Chemical abundances

An example science case is given by the ongoing debate around the chemical abundance discontinuity between the ionized gas in the H II regions (as probed by optical emission lines) and the neutral gas (as probed by FUV absorption lines) of blue compact dwarf galaxies (BCDs). This debate is well illustrated by several studies of the BCD I Zw 18 (18 Mpc, $\approx 2\%$ solar metallicity). Early observations with HST/GHRS showed a discrepancy between the oxygen abundance measured in emission and in absorption, leading to the hypothesis of self-enrichment by the current starburst episode (Kunth & Sargent 1986; Kunth et al. 1994) but, due to a limited sensitivity, only strong lines were accessible and hidden saturation could not be identified easily (Pettini & Lipman 1995). Later studies of the same galaxy with FUSE highlighted issues regarding the (stellar) continuum placement and the selection of weak lines (Aloisi et al. 2003) and showed that only a small discrepancy may exist, if any (Lecavelier des Etangs et al. 2004). More recently, Lebouteiller et al. (2013) confirmed, using HST/COS and weak lines such as λ1254 S II, that a small discrepancy does exist in I Zw 18. A sample analysis of BCDs by Lebouteiller et al. (2009) showed that an overall metallicity floor of $\sim 2\%$ solar may exist for galaxies in the nearby Universe which could be linked to the intergalactic medium (IGM) enrichment. Metallicity discontinuity between the ionized and neutral phases seem to occur for moderately metal-poor ($10-50\%$ solar) galaxies which could be due to dilution by metal-poor/free gas in the halos rather than by self-enrichment in the H II regions. Progress on this topic has been limited by the lack of sensitivity (resulting in a small sample) and the lack of spectral and spatial resolution (resulting in important biases in the column density determinations).

2.2 Star-forming gas reservoir at low metallicity

FUV observations of nearby low-metallicity galaxies also shed a light on the molecular gas, which, despite the strong star-formation episode occurring in these galaxies, often remains elusive. While it is expected that CO emission is globally weaker because of abundance effects and selective photodissociation of CO in a dust-poor environment (e.g., Wolfire et al. 2010; Schruba et al. 2012), the lack of diffuse H_2 detections in the FUV (e.g., Vidal-Madjar et al. 2000) is explained by enhanced photodissociation and a larger critical surface density for H_2 formation (Hoopes et al. 2004; Sternberg et al. 2014).

Dense H_2 clumps that may be the seeds for star-formation at low-metallicity also remain difficult to observe. ALMA detections of CO clouds in moderately metal-poor galaxies (e.g., Rubio et al. 2015, Shi et al. in preparation) indicate that molecular gas must exist in dense clumps of size $\lesssim 1$ pc that we should be able to identify at lower metallicities thanks to near-infrared observations of warm H_2 layers (e.g., Thuan et al. 2004; Lebouteiller et al. 2017). FUV absorption H_2 measurements so far have been limited to translucent clouds while LUVOIR should be able to access truly molecular clouds ($A_V \gtrsim 5$). The POLLUX instrument in particular enables the determination of the physical properties of these molecular clouds (temperature, density, magnetic field, dust-to-gas mass ratio) as a function of the environment (e.g., Milky Way vs. low-metallicity galaxies, quiescent vs. active star-formation).

Finally, thermal processes can be investigated through the use of fine-structure cooling lines such as C II*, O I*, O I**, Si II*... Such tracers give valuable information on the ionization degree, temperature, and density of the neutral star-forming gas reservoir and provide indirect constraints on the gas heating mechanisms (photo-electric effect on dust grains, photoionization by FUV or X-ray photons, shocks...) and on the consequences for the regulation of star formation. Fine-structure absorption lines have been observed in and around the Milky Way, in Damped Lyman-α systems (shifted to the optical domain), and a few nearby BCDs (e.g., Lehner et al. 2004; Wolfe et al. 2003; Howk et al. 2005; Lebouteiller et al. 2013, 2017) but the number of Si II* and O I** detections (required for instance to measure the gas temperature) remain small due to limited sensitivity.

3 Summary

In summary, LUVOIR enables the observations of the ISM toward individual sources within the Milky Way and nearby galaxies. This in turn enables the tomography of chemical abundances, kinematics, and physical conditions in the same fashion as IGM tomography of the Lyman-α forest toward background quasars. The combination of high spatial resolution allowed by LUVOIR and high spectral resolution allowed by POLLUX will mark an era of exquisite detailed science in the Milky Way (properties of molecular clouds, molecule formation pathways, origin and distribution of phases...) and detailed studies of the ISM properties in different environments (dust grain composition, chemical enrichment, gas heating mechanisms...).

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