Pathways through interstellar matter:
From the closest stars to the most distant quasars

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Abstract. Observations of quasar absorption systems relevant for studies of
star formation at redshift $2 \lesssim z \lesssim 4$ are briefly reviewed. Emphasis is given on
the role played by dust in our understanding of the star formation history of
galaxies detected as absorption systems. Local interstellar studies are used as a
reference for understanding the properties of high redshift interstellar media.

1. Introduction

The interstellar medium is relevant for two galactic processes discussed in the
present conference: (1) provides the gas that feeds star formation and (2) col-
lects the feedback from stellar radiation and ejecta. The present contribution is
focussed on interstellar observations obtained from absorption line spectroscopy
of nearby stars and distant quasars. Thanks to their brightness, nearby stars of-
fer the possibility to study the local interstellar medium in detail since they can
be observed at high spectral resolution from space. High resolution is required
because interstellar lines are generally narrow; space instrumentation allows us
to detect the most important interstellar absorption lines, which lie in the ul-
traviolet spectral range. The local interstellar medium serves as a paradigm for
interstellar studies of distant galaxies. The diffuse gas of high redshift galaxies
can be probed by means of high resolution spectroscopy of quasars. Thanks to
the expansion of the Universe, many ultraviolet interstellar absorption lines of
the intervening galaxies are redshifted to the optical spectral range, where they
can be studied in detail in high resolution quasar spectra collected with 10-m
class telescopes.

The fact that this conference serves as a celebration of the astrophysical
career of John Beckman offers me the opportunity to recall, in the first part of
my talk, some of the local interstellar studies that I had the pleasure of doing in
collaboration with John during his first years at the Instituto de Astrofísica de
Canarias. In the second part I will review some recent work on the interstellar
media of high redshift galaxies observed as quasar absorption line systems.

2. Pathways to nearby stars

Interstellar absorption lines were discovered accidentally, as the result of studies
of high resolution stellar spectroscopy: Ca II interstellar lines were first identified
in the spectrum of δ Ori because they did not share the photospheric radial ve-
locity curve of this binary star (Hartmann, 1904). It is less known that the Mg II
interstellar lines of the very local gas ($\lesssim 10$ pc from the Sun) were discovered accidentally in the Mg $\text{II}$ chromospheric emissions of the cool star $\beta$ Hyi, in the framework of a collaboration between John Beckman, newly arrived at the IAC, and the Trieste group of stellar spectroscopy (Vladilo et al. 1985). The claim for detection of interstellar Mg $\text{II}$ was based on the velocity separation between the photospheric/chromospheric lines and the projected velocity vector of the interstellar medium, predicted from previous studies of the gas within $\sim 10^2$ pc from the Sun (Crutcher 1982). Observations taken with the *International Ultraviolet Explorer* (IUE) confirmed the interstellar nature of the Mg $\text{II}$ absorptions detected at the edges of the stellar chromospheric emissions (Molaro, Vladilo & Beckman 1986). Having developed this method of identification of local Mg $\text{II}$ lines in late-type stars, we analysed the full IUE spectroscopic database and produced a map of the interstellar gas at $\lesssim 30$ pc from the Sun (Genova et al. 1990). We found that the nearby gas is very inhomogeneous, with regions of low density, in the direction of the Galactic anticenter and the Galactic poles, and regions of high density, in the direction of the Galactic center.

As a result of the ISM kinematics and of the inhomogeneous distribution of the gas, the local Mg $\text{II}$ interstellar absorption shows remarkable spatial variations in radial velocity and intensity which confuse the analysis of the stellar Mg $\text{II}$ chromospheric lines. As a by-product of our analysis of the local gas, we were able to perform a study of the Mg $\text{II}$ chromospheric emission profiles uncontaminated by interstellar absorption (Vladilo et al. 1987). A lesson learnt from this investigation is that one should beware of the subtle effects introduced by the intervening medium on the observed properties of any class of astronomical objects. If this is true for nearby stars, one should be concerned about studies of distant quasars, as we discuss in the next part of this talk.

The velocity vector of the local interstellar medium is material which has been shocked and accelerated by stellar winds and supernovae associated with the Sco-Oph OB association (Crutcher 1982). This is an example of how the interstellar medium bears the signature of stellar feedback and therefore can be used to trace the history of star formation in galaxies. In the next section we will show other examples of the connection between physical properties of the interstellar medium and star formation.

### 3. Pathways to distant quasars

As originally predicted by Bahcall & Salpeter (1965), quasar spectra show absorption line systems originating in the diffuse gas that lie along the path to the quasar. The study of these spectra allows us to probe the physical and chemical properties of the intergalactic/interstellar medium over a large fraction of the Hubble time, back to the epoch of quasar formation, with an accuracy comparable to that achievable in UV studies of the local interstellar medium mentioned in the previous section.

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1 Early-type stars provide a better background for the detection of interstellar absorptions than late-type stars; however, they are too rare within $\sim 30$ pc.
Quasar absorbers are classified according to their H\textsc{i} column density, $N(\text{H}\textsc{i})$, and to the presence of metal lines at the same redshift of the Ly\,$\alpha$, if any. The weak Ly\,$\alpha$ lines, with column densities $10^{12} \lesssim N(\text{H}\textsc{i})$ [atoms cm$^{-2}$] $\lesssim 10^{16}$ are very numerous and produce a “forest” of narrow absorptions in the spectral region bluewards of the Ly\,$\alpha$ emission; no metal lines are directly associated with these absorbers. At the other extreme of the column density distribution, we have the strong Ly\,$\alpha$ lines with $N(\text{H}\textsc{i}) \geq 2 \times 10^{20}$ atoms cm$^{-2}$, which are instead very rare and always associated with metal lines of high and low ionization species. These absorbers are called “damped Ly\,$\alpha$” (DLA) systems (Wolfe et al. 1986), because the Ly\,$\alpha$ line profile shows “damping wings”, due to natural broadening, that extend beyond the doppler core. There is common consensus that DLA systems originate in the interstellar medium of intervening galaxies (hereafter “DLA galaxies”). A recent review on DLA systems can be found in Wolfe, Gawiser & Prochaska (2005). Here we focus on the effects of dust on our understanding of the star formation history of DLA galaxies.

By analogy with studies of nearby galaxies, we expect interstellar dust to be a pervasive component of DLA galaxies. The observational evidence for the existence of dust in DLA systems is slowly growing in the course of the years. At low redshift, definitive evidence has been found in the DLA system at $z = 0.52$ towards AO 0235+164, where the dust extinction bump at 2175 Å and the silicate absorption at 9.7 µ have been detected (Junkkarinen et al. 2004; Kulkarni et al. 2007). The evidence for dust in the bulk of the DLA population is mainly based on studies of elemental depletions: by analogy with local interstellar studies we expect refractory elements, such as Fe or Cr, to be depleted from the gas phase, where they can be detected via absorption spectroscopy, to the dust component, where they escape detection with this technique; we instead expect volatile elements, such as Zn or S, to be undepleted. Evidence for differential depletion in DLA systems have been confirmed by many studies (Pettini et al. 1997, 2000; Hou, Boissier & Prantzos 2001; Prochaska & Wolfe 2002; Vladilo 1998, 2004; Dessauges-Zavadsky et al. 2006). The existence of general trends between depletion, metallicity and H$_2$ molecular fraction (Ledoux, Petitjean, & Srianand 2003; Petitjean et al. 2006) indicate that the observed depletions are indeed due to dust, rather than to anomalous DLA abundance patterns.

To probe the properties of the high redshift dust in DLA galaxies it is important to complement the studies of differential depletion with studies of quasar extinction. From our knowledge of local dust, we expect the extinction to become more efficient with decreasing wavelength and to produce a reddening of the quasar continuum. The measurement of quasar reddening due to individual DLA systems is quite challenging (Ellison, Hall & Lira 2005); reddening detections have been obtained so far for a few metal rich systems at redshift $z \lesssim 2$ (Vladilo et al. 2006). The detection of the mean quasar reddening due to Ca $\textsc{i}$ systems (Wild, Hewett & Pettini 2006) and Mg $\textsc{ii}$ systems (York et al. 2006; Menard et al. 2007) at $z \lesssim 1$ suggests that also for DLA systems should it be possible to obtain a statistical detection. A claim of detection based on the analysis of a sample of 13 DLA/QSOs (Pei, Fall & Bechtold 1991) was not confirmed by the study of a large set of Sloan Digital Sky Survey (SDSS) spectra of the 2nd data release (Murphy & Liske 2004). Analysis of the photometric and spectroscopic database of the 5th SDSS data release indicates that the mean quasar reddening due to DLA systems at $2.2 \lesssim z \lesssim 3.5$ has been detected; the
low value of dust-to-gas ratio obtained, \( \langle A_V/N(\text{HI}) \rangle \sim 3 \times 10^{-23} \) mag cm\(^{-2}\), is in line with the low level of metallicity of these systems (Vladilo, Prochaska & Wolfe 2007).

### 3.1. Dust and star formation in DLA systems

The techniques used to determine the star formation rate (SFR) based on the measurement of emission lines are ineffective in DLA systems. This is due to the difficulty of disentangling the DLA galaxy against the quasar PSF. Only in a few DLA systems has it been possible to derive limits, in the order of a few \( M_\odot \) year\(^{-1}\), from studies of the Ly\(\alpha\) (Møller, Fynbo & Fall, 2004) or H\(\alpha\) (Kulkarni et al. 2001) emission. A value larger by one order of magnitude was derived in one DLA system at \( z = 1.9 \) from the analysis of the FUV continuum (Møller et al. 2002). The paucity of these measurements indicates the need of especially designed techniques aimed at determining the SFR in DLA systems.

A method developed by Wolfe, Prochaska & Gawiser (2003) makes use of the column density of the C\(\text{II}^*\) 1335.7 Å line to determine the [C\(\text{II}\)] 158 \(\mu\)m cooling rate. Assuming thermal balance one can estimate the heating rate and so constrain the efficiency of the heating mechanisms. The main heating mechanism considered is photoelectric emission from dust grains. The efficiency of this mechanism depends on the intensity of the interstellar radiation field, which in turn is related to the SFR. With this method two SFR solutions can be found, corresponding to the thermally stable states of a two-phase medium with a cold neutral medium (CNM) in pressure equilibrium with a warm neutral medium (WNM). The average SFR per unit area found for 23 DLA systems with detected C\(\text{II}^*\) line is \( \langle \dot{\psi}_\ast \rangle \simeq 11 \times 10^{-3} \) \(M_\odot\) year\(^{-1}\) kpc\(^{-2}\) for the CNM solution; the larger value found for the WNM solution, \( \langle \dot{\psi}_\ast \rangle \simeq 0.21 \) \(M_\odot\) year\(^{-1}\) kpc\(^{-2}\), implies a bolometric background in excess of the observational limits (Wolfe et al. 2004). Since the efficiency of the heating mechanism considered in these computations depends on the amount of dust present in the medium, an accurate estimate of the dust-to-gas ratio is necessary to infer an accurate value of SFR from the C\(\text{II}^*\) 1335.7 Å column densities.

If the Kennicutt-Schmidt law is valid at high redshift, one can estimate the SFR in DLA systems from the measured H\(\text{I}\) column densities. This can be done by taking into account inclination effects to convert the \( N(\text{HI}) \) into the column density perpendicular to the galactic disk, \( N_\perp \), which is used in the law \( \langle \dot{\psi}_\ast \rangle_\perp = K (N_\perp / N_\odot)^{\beta} \) (Kennicutt 1998). From this type of calculation, Wolfe & Chen (2006) find that 3\% of the sky should be covered with extended objects brighter than \( \mu_V \sim 28.4 \) mag arcsec\(^{-2}\), if DLAs at redshift \( z \in [2.5, 3.5] \) undergo in situ star formation. To test this hypothesis these authors searched for low-surface brightness features in the Hubble Ultra Deep Field (UDF). They found upper limits on the comoving SFR densities that are between factors of 30 and 100 lower than predictions, suggesting a reduction by more than a factor of 10 in the star formation efficiency predicted by the Kennicutt-Schmidt law at \( z \sim 3 \). This type of conclusion maybe affected to some extent by the presence of dust: the extinction would yield a lower observed intensity and hence a lower value of the constant \( K \) inferred with this method.

Constraints on the SFR history of DLA galaxies can also be obtained by comparing the elemental abundances measured from the spectra with those pre-
dicted by the models of galactic chemical evolution (e.g. Matteucci, Molaro & Vladilo 1997). Abundance ratios can be used as diagnostics of evolution if they involve two elements synthesized on different time-scales, such as α-capture elements, mainly produced by type II SNe, and iron-peak elements, mainly produced by type Ia SNe. The α/Fe ratio ratio, when compared with a metallicity tracer, such as Fe/H, allow us to clarify the particular history of star formation involved. In a regime of high SFR we expect to observe enhanced α/Fe ratios for a large interval of Fe/H, while the opposite is expected for a regime of low SFR (Matteucci 1991). In applying this type of study to DLA systems we face the problem that the measured abundance ratios may be affected by differential depletion. In fact, the α/Fe ratios measured in DLA systems are often enhanced due to differential depletion, as it is the case of the Si/Fe ratios. This apparent enhancement mimics the behaviour of galaxies with relatively high SFR. However, when depletion effects are taken into account (Vladilo 2002) or volatile elements are used in the analysis (Centurión et al. 2000), or dust-free DLA systems are investigated (e.g. Molaro et al. 2000) the resulting α/Fe ratio is generally not enhanced. The comparison with chemical evolution models suggests an origin of DLA systems in galactic regions with low or episodic SFR (Calura, Matteucci & Vladilo 2003; Dessauges-Zavadsky et al. 2006).

The presence of dust may also affect our understanding of the star formation history of DLA systems due to the extinction of the quasar continuum. In the most extreme cases, the extinction due to dust-rich DLA systems could lead to the obscuration of the quasar (Ostriker & Heisler 1984; Fall & Pei 1989, 1993). In general, the extinction may induce a selection bias acting against the detection of dust-rich galactic regions in magnitude-limited surveys (Boissé et al. 1998; Prantzos & Boissier 2000; Vladilo & Péroux 2005). Studies of radio-selected quasars surveys, not affected by extinction, suggest that the impact of this effect on the statistical properties of DLA systems is modest (Ellison et al. 2001; Jorgenson et al. 2006), but the size of these surveys is not large enough to reach firm conclusions. Due to the extinction bias, the mean DLA metallicity of magnitude-limited surveys may be underestimated since the dust-rich regions that are missed are likely to originate in metal-rich systems. In particular, the H i-column density weighted metallicity \( \langle M/H \rangle_w = \frac{\sum_i (M/H)_i \times N_i(\text{HI})}{\sum_i N_i(\text{HI})} \), an indicator of the mean cosmic metallicity at high redshift (Lanzetta, Wolfe & Turnshek 1995) may be underestimated. The weighted metallicity \( \langle M/H \rangle_w \) can be used to infer the global rate of star formation of the Universe at high redshift (Pei & Fall 1995; Pei, Fall & Houser 1999). If \( \langle M/H \rangle_w \) is underestimated also the global SFR is underestimated. Present estimates of this bias are still open to debate (Akermann et al. 2005, Vladilo & Péroux 2005).

### 3.2. Are we missing the regions of high SFR?

The study of the metallicities versus H i column densities indicates that DLA systems are concentrated below the value of metal column density \([\text{Zn/H}] + \log N(\text{H} \ i) \sim 20.5\) (Boissé et al. 1998). Interstellar regions with metal column

\(^2\) Zinc is used as a tracer of the metals since it is believed to be undepleted. We adopt the usual definition of metallicity relative to the solar value \([X/H] \equiv \log N(X)/N(\text{H}) - \log(X/H)_\odot\).
Figure 1. Metallicity versus $\text{H} \text{i}$ column density in DLA galaxies predicted by a cosmological simulation (Nagamine et al. 2004; model Q5). Crosses: systems extracted at random from the simulation. Circles: systems observable in a DLA-QSO survey with limiting magnitude $r = 19$. An SMC-type extinction curve has been adopted to obtain the extinction in the observer's frame. Dashed line: empirical threshold $[\text{Zn}/\text{H}] + \log N(\text{H} \text{i}) = 20.5$.

densities above this empirical threshold are instead predicted to exist at high redshift by models of galactic chemical evolution (Prantzos & Boissier 2000; Churches, Nelson & Edmunds 2004) and by SPH cosmological simulations of DLA galaxies (Cen et al. 2003; Nagamine et al. 2004). The lack of observed DLA systems at $[\text{Zn}/\text{H}] + \log N(\text{H} \text{i}) > 20.5$ has been attributed by some authors to the extinction bias, that would affect DLA systems with high metallicity and $N(\text{H} \text{i})$ (Boissé et al. 1998; Vladilo & Péroux 2005). If this hypothesis is correct, we would be missing the regions of high star formation rate. The relation between interstellar extinction, $A_\lambda$ [mag], and metal column density is fundamental to test this hypothesis. Adopting iron as an indicator of metallicity, one can derive the following expression for the $V$-band extinction in the rest frame of the absorber

$$A_V = \langle s_{V}^{\text{Fe}} \rangle \times f_{\text{Fe}} \times (\text{Fe}/\text{H}) \times N(\text{H} \text{i}) ,$$

where $(\text{Fe}/\text{H})$ is the total abundance by number of iron (gas plus dust), $f_{\text{Fe}}$ is the fraction of iron in dust form, and $\langle s_{V}^{\text{Fe}} \rangle$ is a line-of-sight average of dust grain parameters (Vladilo et al. 2006). Empirical estimates of $\langle s_{V}^{\text{Fe}} \rangle$ yield a typical value $\langle s_{V}^{\text{Fe}} \rangle \approx 3 \times 10^{-17}$ mag cm$^2$ in $\text{H} \text{i}$ interstellar clouds, metal absorption
systems and a few DLA systems at \( z_a \lesssim 2 \) (Vladilo et al. 2006). By adopting this value of \( \langle s^F_{\text{Fe}} \rangle \), together with an empirical estimate of \( f_{\text{Fe}} \) (Vladilo 2004), we can use relation (1) to compute the extinction expected for DLA systems of given metal column density. This type of calculation can be applied, for instance, to test the predictions of SPH cosmological simulations. For each DLA system found at random in the cosmological box one enters the \( N(\text{H} \text{I}) \) and \( (\text{Fe}/\text{H}) \) predicted by the simulation and estimates the rest-frame extinction \( A_V \). The extinction in the observer’s frame is then obtained adopting a normalized curve of interstellar extinction, \( \xi(\lambda) = A_\lambda/A_V \). This extinction is added to the magnitude of a simulated quasar, which is assigned at random to each line of sight according to the known frequency distribution of quasar magnitudes. Lines of sight with dimmed magnitude in excess of a given magnitude limit are then discarded from the mock sample. An example of result of this type of computation is shown in Fig. 1 for a mock survey of DLA systems at \( z \simeq 3 \) with limiting magnitude \( r = 19 \). This value is representative of the current magnitude limit of high spectral resolution metallicity surveys. One can see in Fig. 1 that the empirical threshold \( [\text{Zn}/\text{H}] + \log N(\text{H} \text{I}) \lesssim 20.5 \) is naturally reproduced by the extinction effect. This result suggests that DLA systems with high SFR are indeed missed. However, even after taking into account the extinction effect, the mean weighted metallicity predicted by the simulation, \( \langle [\text{M}/\text{H}]_w \rangle \simeq -0.85 \) dex, is too high compared to the one measured in metallicity surveys at \( z \simeq 3 \), \( \langle [\text{M}/\text{H}]_w \rangle \simeq -1.5 \) dex (Prochaska, Gawiser & Wolfe 2001). This discrepancy indicates that the SFR predicted by the cosmological simulation is too high. More refined simulations, with improved physics of star formation, are required before this method can be used to quantify the fraction of regions of high SFR missed due to the extinction bias.

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