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Part 1

THE ABSORBER–GALAXY CONNECTION

‘星’ — xīng — ‘star’, and used in the word for galaxy — ‘星系’ — xīng xì


星

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The connections between QSO absorption systems and galaxies: low-redshift observations

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Abstract. Quasar absorption lines have long been recognised to be a sensitive probe of the abundances, physical conditions, and kinematics of gas in a wide variety of environments including low-density intergalactic regions that probably cannot be studied by any other means. While some pre-*Hubble Space Telescope (HST)* observations indicated that Mg II absorption lines arise in gaseous galactic halos with a large covering factor, many early QSO absorber studies were hampered by a lack of information about the context of the absorbers and their connections with galaxies. By providing access to crucial ultraviolet resonance lines at low redshifts, deployment of *HST* and the *Far Ultraviolet Spectroscopic Explorer* enabled detailed studies of the relationships between QSO absorbers and galaxies. The advent of large surveys such as the *Sloan Digital Sky Survey (SDSS)* has also advanced the topic by greatly improving the size of absorber and galaxy samples. This paper briefly reviews some observational results on absorber-galaxy connections that have been obtained in the *HST/SDSS* era, including Mg II absorbers, the low$-z$ Lyα forest, Lyman limit and damped Lyα absorbers, and O VI systems.

1. Introduction

1.1. *Some advantages of QSO absorption lines*

Absorption-line spectroscopy is a powerful tool for the study of gas in the Universe. A wide array of elements can be detected in absorption; in the Milky Way ISM, absorption lines ranging from common elements (e.g. H, C, N, O) to exotic heavy metals (e.g. arsenic, selenium, tin, and lead, see e.g. Cardelli *et al.* 1991, 1993; Hobbs *et al.* 1993) have been detected. With adequate signal-to-noise, these exotic species can in principle be observed in higher column density QSO absorbers as well (Prochaska, Howk & Wolfe 2003). Abundance patterns in QSO absorption systems provide valuable information on the nucleosynthetic origins and dust content of the gas, and the buildup of metals vs. time. QSO absorption lines also probe the physical conditions of interstellar and intergalactic material: line widths, excited fine-structure lines, and column density ratios yield good constraints on the temperature, density, pressure, and ionisation mechanism as well as the radiation field to which the gas is exposed.

Possibly the greatest advantage of absorption spectroscopy, however, is its tremendous sensitivity. QSO absorption lines can be used to detect low-density gas that is orders of magnitude below the detection threshold of most other techniques. As an example, Fig. 1 shows absorption lines detected at $z_{\rm abs} = 0.19193$ in a UV echelle spectrum of the bright QSO PHL1811 (Jenkins *et al.* 2003) obtained in a modest *HST* programme with the Space Telescope Imaging Spectrograph (STIS). The H I Lyα absorption line shown in the top panel of Fig. 1 has log N(H I) = 12.8 and is detected at the 4σ level. For comparison,

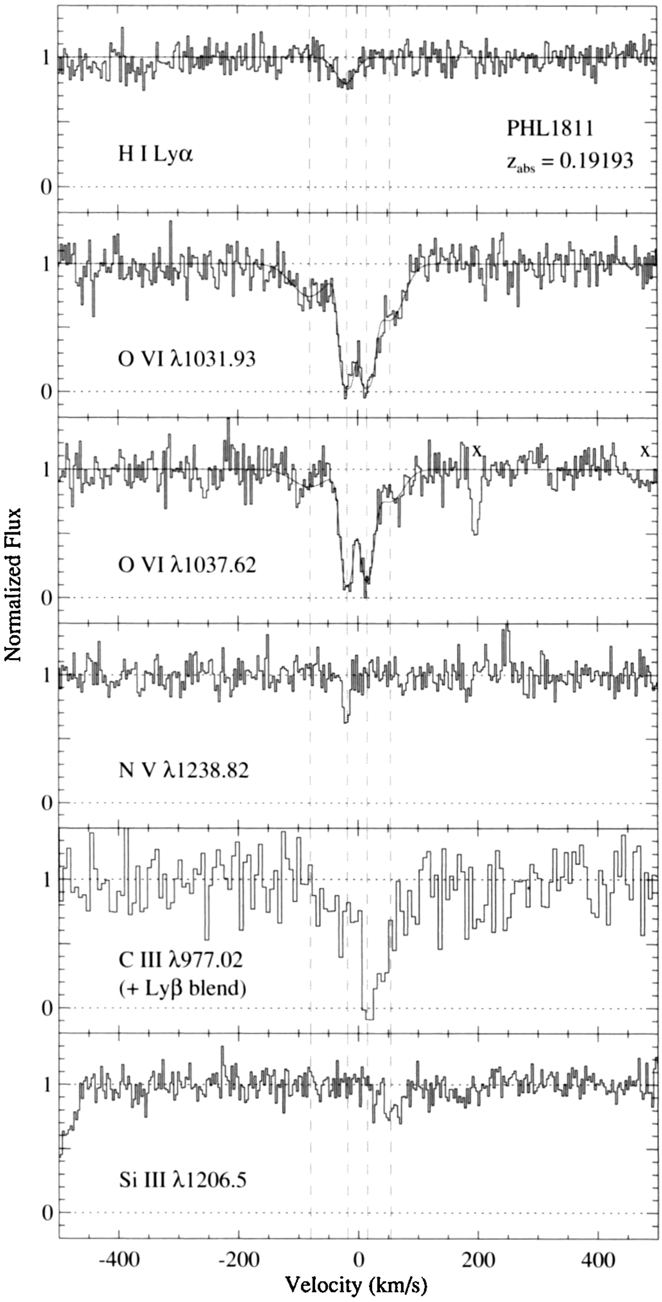

Figure 1. A complex, multi-component O VI absorption system detected in the UV spectrum of PHL1811 obtained by Jenkins *et al.* (2005) with the STIS E140M echelle spectrograph. The panels show the continuum-normalised profiles of several species of interest plotted vs. velocity in the absorber frame ($v = 0$ at $z_{\rm abs} = 0.19193$). Multiple components are unambiguously detected in this absorber, and moreover, the physical conditions and/or metallicity of the gas change dramatically from one component to the next (compare the relative strengths of H I, C III, Si III, N V, and O VI). The high spectral resolution provided by STIS is crucial for successful analysis of complex absorption systems such as this one.

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21 cm emission can be used to study H I-bearing gas, and with considerable effort, gas with log N(H I) > 18.0 can be detected in 21 cm emission. For the study of H I, high-resolution spectra are typically five or six orders of magnitude more sensitive than 21 cm emission observations. Moreover, absorption lines can be measured comparably well from $z = 0$ out to $z > 4$ while 21 cm emission can only be detected in the nearby Universe with current facilities. And absorption is not limited to low-density, weak absorption lines: high column densities can be measured with great precision as well because these cases show broad damping wings spread over many pixels. Intrinsically weak lines (e.g. spin-changing transitions such as the O I 1355.6 Å line) can also be used to measure abundances in high column density and/or high metallicity systems in which the usual resonance lines are strongly saturated but not strong enough to show damping wings.

However, QSO absorption systems can be complex, and in order to take full advantage of the technique, high spectral resolution and broad wavelength coverage are required. Fig. 1 again provides good examples of absorber complexity and the benefits of high resolution with broad coverage. Comparing the various panels in Fig. 1, it is readily apparent that there is more to life than H I – Lyα only reveals the tip of the iceberg in this system. Four components are evident in the O VI doublet at $v = -80, -18, +15$, and $+54$ km s^{-1}. Lyα is only detected at -18 km s^{-1} along with N V, weak C III, and O VI. This is also the only component to show N V. On the other hand, the Si III λ1206.5 line appears to be detected only in a different component (at $v = +54$ km s^{-1}) with no corresponding Lyα line. Evidently, the physical conditions and metallicity at $v = +54$ km s^{-1} make Si III and O VI detectable without any obvious associated Lyα or N V. At first glance, C III appears to be strongest at yet a different velocity. However, because the STIS spectrum covers a substantial wavelength range, we realise that a strong Lyα system is present at a different redshift, one that shifts its Lyβ line into a blend with the C III line shown in Fig. 1. Thanks to the high spectral resolution of the data, we can decompose this C III/Lyβ blend and at least provide useful constraints based on the C III line. Indeed, at lower resolution, these lines in Fig. 1 could still be detected (with adequate signal-to-noise), but such data would not allow the column densities to be correctly assigned to different components, which could lead to erroneous conclusions. High spectral resolution provides many other benefits, e.g. better ability to assess and correct for line saturation and better ability to measure widths of narrow lines such the N V line in Fig. 1.

1.2. *Some disadvantages of QSO absorption lines*

However, like all observational techniques, QSO absorption lines have some drawbacks. For example, faint QSOs are difficult to observe at high resolution – especially at lower redshifts – which limits sample sizes. The main disadvantage, however, is that the technique only provides information about material along the pencil beam to the background QSO. At higher redshifts, it is extremely challenging to understand how the detailed information provided by quasar absorption measurements is really connected with the more global context, e.g. whether the absorption arises in the IGM or the ISM of a galaxy, what type of galaxy, etc. However, at low redshifts, detailed information about the environment in which the absorption occurs can be obtained, information such as redshifts and deep images of nearby galaxies, 21 cm or CO emission maps, and the locations of nearby galaxy groups/clusters, voids, and large-scale structures. With such knowledge, we can hope to understand the real nature of QSO absorption lines and their implications for galaxy evolution and cosmology.

The purpose of this paper is to present some examples of how studies of the connections between low-redshift absorbers and galaxies have so far advanced our understanding of

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the topic as well as goals for future work. This brief (and incomplete) review will comment on studies of low-z Mg II absorbers, Lyα clouds, systems with higher H I column densities, and O VI absorbers.

2. Mg II absorbers

Historically, the study of QSO absorber-galaxy relationships began with Mg II absorption systems. Magnesium is not particularly abundant and moreover is prone to confusion from dust depletion and ionisation effects, so in hindsight, Mg II seems like a strange species to use for probing the galaxy-absorber connection. However, this choice was strongly driven by practical constraints: before the deployment of *HST*, only Mg II could be studied from the ground at redshifts low enough to allow follow-up investigation of nearby galaxies. Among the dominant ions in H I gas, Mg II is the species with the longest-wavelength resonance transitions, the Mg II doublet at $\lambda\lambda2796.35$, 2803.53. Intrinsically more useful species (e.g. H I or O I) only have resonance transitions at $\lambda \ll 2000$ Å, and ions with resonance lines in the optical (e.g. Na I or Ca II) are even more difficult to analyse than Mg II.

The first observational test of the Mg II - galaxy connection was to image the field around a QSO with a known Mg II system and then measure the redshifts of galaxies close to the line of sight to search for objects at the redshift of the absorption system. Such observations were pioneered by Bergeron (1986), Bergeron *et al.* (1987), Cristiani (1987), and Bergeron & Boissé (1991). These early studies successfully found galaxies at the Mg II absorption redshifts and at relatively small impact parameters. The investigation of Mg II systems with the largest sample, however, was done by Steidel and collaborators, who found that all normal galaxies with luminosities $L^*(B)$ had Mg II absorbing halos of radius $R^* \sim 60\ h_{70}^{-1}$ kpc, and that the radius of a halo scales weakly with galaxy luminosity (Steidel *et al.* 1994; Steidel 1994). These studies appeared to establish a direct link between an individual galaxy and a Mg II absorption system. However, the nature of this link remains unclear. Steidel *et al.* (2002) have compared the kinematics of five Mg II absorbers with the rotation curves of nearby ($\rho \leqslant 110 h_{70}^{-1}$ kpc) inclined galaxies, and they conclude that most of these Mg II systems arise in rotating halo gas associated with the nearby galaxy. On the other hand, Churchill, Steidel & Vogt (1996) have compared high-resolution Mg II absorption recordings to high-quality *HST* observations of nearby galaxies, and they find no compelling correlations between the absorber properties and the nearby galaxy properties. Further comments and more recent results on Mg II absorber - galaxy relationship studies are found in Churchill, Kacprzak & Steidel (2005). It now appears likely that Mg II systems have a variety of origins, and more observations are needed.

More vigorous comparison of observations to theoretical work on gas in galaxies is also required. Over the last decade, theorists have produced detailed hydrodynamical simulations which trace the growth of large-scale structure in the Universe and predict the emergence of a ‘cosmic web’ of filaments connected at nodes where galaxy clusters are found. The filamentary distribution of galaxies has been abundantly verified by large galaxy redshift surveys such as 2MASS (e.g. Maller *et al.* 2003), SDSS (e.g. Stoughton *et al.* 2002), and 2dFGRS (e.g. Colless *et al.* 2001), but observations of gas in the web are much more sparse. Indeed, these models would seem to require a re-assessment of how absorbing gas and galaxies might be connected. In the dark matter halos and filaments, gas and galaxies share the same gravitational potentials — and so would be found at similar redshifts — but the exact interplay between a galaxy and the intergalactic medium (IGM) is poorly understood. On the one hand, the $z < 1$ IGM may

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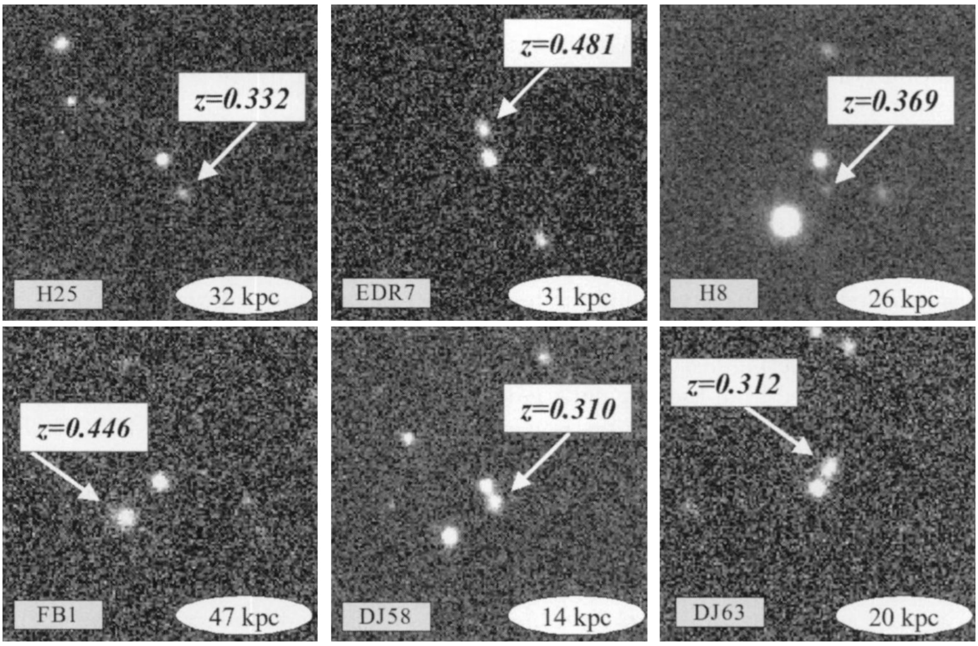

Figure 2. Sections from six SDSS r-band images showing some of the QSO-galaxy pairs studied. The background QSO is the bright stellar-like source at the centre of each image, and the intervening foreground galaxy is identified with an arrow. The measured redshifts are indicated. The separation between the galaxy and the QSO sight-line is indicated at the bottom-right of each panel, in units of h_{70}^{-1} kpc. Each image is 1 arc-min on a side.

be metal-enriched through much earlier episodes of star-formation [e.g. winds from the first galaxies (Aguirre *et al.* 2001), population III stars, etc.] so the presence of a galaxy is not a necessary condition for the existence of metallic (absorbing) gas. On the other hand, galaxies probably continue to enrich the IGM from their formation through to the present (Heckman *et al.* 2000) via a variety of processes, including: winds from starburst and blue compact dwarf galaxies, the more normal expulsion of interstellar gas via galactic chimneys, tidal stripping through galaxy-galaxy interactions, the evaporation of dwarf galaxies, or ram-pressure stripping from passage through an intra-group/intra-cluster medium.

So what do Mg II systems represent in this new paradigm of galaxies embedded in the cosmic web? There seems little doubt that galactic *disks* give rise to strong Mg II lines since disks have a substantial N(H I) and relatively high metallicity over a large cross-section of a galaxy. Our own Milky Way, for example, produces complex, saturated Mg II absorption along all sight-lines which penetrate (only half of) the Galactic disk (e.g. Bowen *et al.* 1995; Savage *et al.* 2000). However, several groups have concluded that rotating disks by themselves are not sufficient to explain the observed Mg II kinematics (e.g. Charlton & Churchill 1998; Steidel *et al.* 2002). Some Mg II absorbers are strong and strikingly symmetric, and this has led to suggestions that these particular systems arise in superbubbles/superwinds (Bond *et al.* 2001; Ellison, Mallen-Ornelas & Sawicky 2003).

2.1. *Do all galaxies cause Mg II absorption?*

This is a fundamental first question. Mg II studies in the late 1980s and early 1990s gave the impression that if a luminous galaxy is within some impact parameter of a background

QSO sight-line, Mg II absorption would almost always be detected. This is somewhat surprising because in the Milky Way, interstellar clouds are small and have a patchy distribution. Most of these early searches for absorbing galaxies were conducted toward QSOs with Mg II systems *which were already known.* Hence, although Mg II absorbers appear to be associated with galaxies in some way, we do not know that *all* galaxies (and/or their environments) give rise to Mg II systems. To address this question, it is worthwhile to invert the procedure originally used to study Mg II-galaxy relationships, i.e. *first* select galaxies close to QSO sight-lines (without any knowledge of the absorption spectrum), *then* search for Mg II lines at the foreground galaxy redshift.

This inverted experiment is useful for testing ideas about how galaxies and the IGM might be connected. If galaxies and QSO absorbers are only loosely associated, the detection rate and covering factor of Mg II around galaxies should be considerably smaller than the 100% found from the original studies. And there should be no correlation with galaxy luminosity. Clearly, if the gas is merely a component of the IGM, then it will be an important challenge to understand the physical state (ionisation, kinematics, and abundances) of such lone clouds. As we discuss below, there are many viable explanations for a low covering factor for Mg II absorbing gas. Nevertheless, a covering factor substantially less than 100% would suggest that the origin of Mg II systems is more complicated than originally thought. Alternatively, if Mg II absorbers do have a near-unity covering factor and adhere to the scaling relationship between radius and luminosity found in the earlier studies, then modelling of galaxy evolution and dynamics would have to take into account the existence of extended and metal-enriched baryonic halos and explain how galaxies can sustain such halos over a significant fraction of their lifetime.

Selecting a significant number of $z > 0.2$ galaxies which lie close on the plane of the sky to QSOs (without forehand knowledge of absorption in the QSO spectrum) is challenging because the galaxies need to be found within $\sim 10''$ of a sight-line to be within a proper distance of $\sim 60\ h_{70}^{-1}$ kpc. The QSO must also be bright enough to be observed spectroscopically at a resolution of only a few Å for the follow-up search for Mg II. Selection of such QSO-galaxy pairs has, until recently, required prohibitively large amounts of observing time. Now, however, the *SDSS* has made such an experiment possible. The wide area of sky covered, the robust identification of large numbers of QSOs, and the availability of multicolour photometry for selection of foreground galaxies ensures that substantial numbers of potential QSO-galaxy pairs can be investigated.

2.2. *Results*

We have been taking advantage of the *SDSS* in order to carry out the inverted Mg II - galaxy study described above. Briefly, we have used multicolour *SDSS* imaging to first select galaxy-QSO pairs; photometric redshifts were used to select galaxies with $z > 0.2$ (so that Mg II could be observed from the ground). While SDSS does obtain follow-up spectroscopy, the galaxies and QSOs in the selected pairs were generally too faint to be covered in the spectroscopic component of the SDSS. Consequently, we have used the *Hobby Ebberly Telescope* to measure the redshifts of thirty $z = 0.31 - 0.55$ galaxies within $14 - 51\ h_{70}^{-1}$ kpc of $g < 20$ QSOs. Fig. 2 shows examples of the SDSS r-band images (from *Data Release 3*) of six such pairs. After the galaxy redshifts were securely measured, in December 2004 we completed a substantial fraction of the second phase of the experiment by using the *Multi Mirror Telescope (MMT)* to observe two thirds of the QSOs at intermediate spectral resolution in order to search for Mg II absorption at the galaxy redshifts. The initial results are surprising. Although all the galaxies lie within the canonical $60\ h_{70}^{-1}$ kpc established as the size of Mg II-absorbing halos, *we find that 50% (10/20) of the QSO spectra show no Mg II lines at the redshifts of the*

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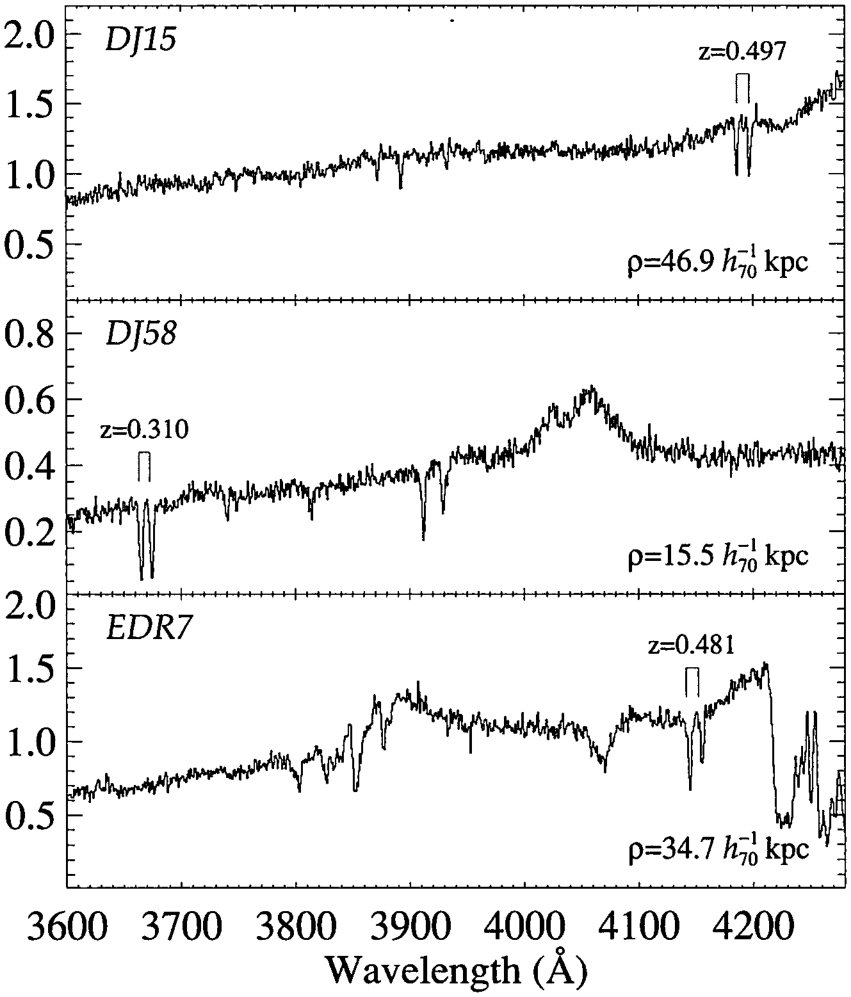

Figure 3. Example *Multi Mirror Telescope* spectra of QSOs whose sight-lines pass close to foreground galaxies. This figure shows relative flux vs. observed wavelength for three cases where Mg II absorption is detected from the foreground galaxy. The expected wavelengths of the Mg II doublet at the redshifts of the intervening galaxies are indicated above each spectrum, and the galaxy sight-line separation is listed at the bottom right of each panel.

intervening galaxies. Fig. 3 shows some examples of our *MMT* spectra in which the Mg II absorption was detected, and Fig. 4 shows cases where no Mg II lines are apparent at the expected wavelength. In both figures, the redshift of the foreground galaxy and the expected wavelengths of the Mg II doublet are indicated above the spectrum, and the projected distance between the galaxy and the sight-line are noted in the lower right corner of the panel.

Could selection effects explain our finding that the detection rate is lower than the 100% expected from earlier studies? Several comments about this issue can be made. First, the non-absorbing galaxies are no fainter than the absorbing ones: all have absolute