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OBSERVATIONS OF H2 IN QUASAR ABSORBERS

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H2 IN SPACE, MEETING HELD IN PARIS, FRANCE
SEPTEMBER 28TH - OCTOBER 1ST, 1999
EDS.: F. COMBES, G. PINEAU DES FORÊTS
CAMBRIDGE UNIVERSITY PRESS, ASTROPHYSICS SERIES

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Observations of H2 in Quasar Absorbers

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The ultraviolet Lyman and Werner absorption lines of H_2 have been searched for in a number of high redshift quasar spectra, and detected unambiguously in at least 3 systems at redshifts $z\sim2$. The lack of detectable H_2 in most absorbers results from the strong selection in quasar studies against lines-of-sight with significant dust extinction. At high redshift, the ultraviolet radiation field is inferred to be higher than that observed in the local solar neighborhood, suggesting that vigorous star-formation is underway in these galaxies.

1. Introduction

Recent observations of the high redshift Universe, interpreted in the context of a new generation of computer simulated model Universes, are providing a clear picture of how large galaxies like the Milky Way formed. A number of different observations suggest that large galaxies were assembled from what appear at $z = 2 - 3$ to be several star-forming proto-galactic fragments (PGF's), widely distributed in space (Windhorst et al. 1994, Pascarelle et al. 1996ab, 1998; Steidel et al. 1996ab, Bechtold et al. 1998). Computer simulations suggest that initially small clumps of material collapsed at the intersection of sheets and filaments in the intergalactic medium, and began forming stars, and that eventually these clumps merged to form large galaxies (Haehnelt, Steinmetz & Rauch 1998, Steinmetz 1998 and references therein). Searches for the galaxies associated with damped Ly-α quasar absorbers show that at $z \sim 2$ they are the same population of objects seen in the Hubble Deep Field faint galaxies and the Lyman dropout galaxies (Steidel et al. 1996ab; Bechtold et al. 1998). They appear to be multiple PGF's, with several clumps of star-formation spread over many megaparsecs.

Since high redshift quasar absorbers are pointers to gas-rich concentrations with active star-formation, they undoubtedly also contain molecular gas. Warm H_2 can be detected through IR emission, but most H_2 is probably contained in a cold phase, measurable by ultraviolet Lyman and Werner absorption (Black & Dalgarno 1976). Shortly after the detection of H_2 absorption in local interstellar clouds with Copernicus in the 1970's (Spitzer et al. 1973), searches for H_2 in quasar absorbers began (Aaronson, Black & McKee 1974; Carlson 1974). However, evidence for molecular gas or dust in quasar absorbers has been scant (Bechtold 1996 and references therein). The inclusion of quasars for absorption studies that are bright and blue selects against lines-of-sight which contain dust, and hence detectable molecular absorption. Note that searches for molecular absorption in the millimeter (reviewed by Combes & Wiklind 1999 and Wiklind & Combes 1999) have been successful only in heavily reddened objects, whose optical/UV continuum is too faint for absorption line spectroscopy.

2. Observations

Table 1 summarizes the searches for H_2 in damped Ly-α quasar absorption systems (from Ge & Bechtold 1999) It includes ground-based spectroscopy, as well as archival data from the *Faint Object Spectrograph* aboard the *Hubble Space Telescope*. Figure 1 shows one of the detections, for the $z(abs) = 2.34$ absorber of the $z(em) = 2.567$ quasar Q1232+0815 obtained at the Multiple Mirror Telescope (MMT). The data and analysis

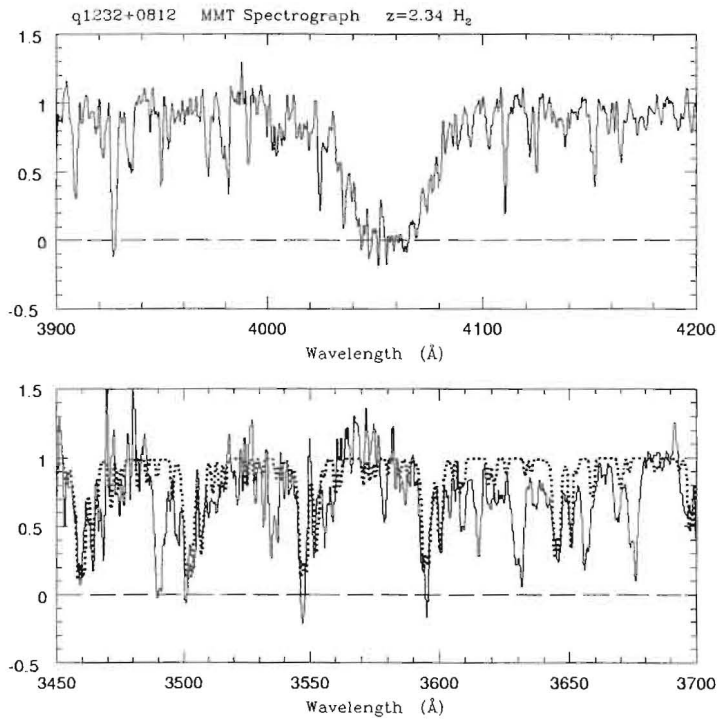

FIGURE 1. Spectrum of QSO 1232+08 obtained with the MMT Blue Spectrograph. Top Panel: Ly-α absorption from intervening system at z=2.34. Bottom Panel: H_2 absorption in the Ly-α forest; dotted lines show model H_2 spectrum. From GBK.

are described in Ge, Bechtold & Kulkarni 2000, hereafter GBK. The top panel shows the Ly-α absorption line, and the bottom panel shows a portion of the molecular hydrogen spectrum, in the Ly-α forest. A cross-correlation analysis with synthetic Ly-α forest spectra shows that the probability that the molecular hydrogen spectrum is produced by the chance superposition of Ly-α forest lines is less than 10^{-4}.

Table 1 gives the H_2 fraction, defined as $f = 2N(H_2)/[2N(H_2) + N(HI)]$ for the quasar absorbers observed to date. The values appear bimodal, with f >0.05 for two cases, and $f << 10^{-4}$ for the rest. This is similar to what was observed in the Copernicus survey of 76 stars in the local solar neighborhood by Savage et al. (1977). They found that f undergoes a transition from $f < 0.01$ to $f > 0.01$ at E(B-V)~0.08 and N(H I + H_2)~ 5×10^{20} cm^{-2}. It isn't possible to derive E(B-V) for quasars in the way one does for stars, but the relative over-abundance of the easily depleted element Cr compared to undepleted Zn, suggests a low dust-to-gas ratio (Table 1). The bimodality of f is understood as the result of self-shielding. Once H_2 begins to form, it shields itself from subsequent photodissociation by ultraviolet radiation, and f increases.

Low extinction is probably not the whole story, however. The lack of molecules in some absorbers may also be the result of an enhanced ultraviolet radiation field. For example, the well-studied absorber of PHL 957 (Q0100+13) has N(HI) = 2.5×10^{21} cm^{-3}, the column density is high enough that H_2 should have been detected (Black, Chaffee & Foltz 1987). They suggested that the lack of H_2 in that system resulted from photodissociation by the ultraviolet radiation field produced by the intense star-formation in the galaxy within which the absorption features arise.

Table 1. **Summary of H_2 from Quasar Absorbers**

QSO	z_{ab}	N(HI)(cm^{-2})	[Zn/H]	[Cr/Zn]	$f^a_{H_2}$	Ref
1328+30	0.69	2.0×10^{21}	−1.2	−0.6	$< 5 \times 10^{-6}$	1,2
0454+03	0.86	6.0×10^{20}	−0.7	−0.1	$< 8 \times 10^{-5}$	1,3
0935+41	1.37	2.5×10^{20}	−1.1	−0.1	$< 2 \times 10^{-4}$	1,4
0013−00	1.97	6.4×10^{20}	−0.8	−1.2	0.22	1,5
0458−02	2.04	8.0×10^{21}	−1.1	−0.7	$< 2 \times 10^{-6}$	1,5
0100+13	2.30	2.5×10^{21}	−1.55	−0.24	$< 4 \times 10^{-6}$	7,8
1232+08	2.34	8.0×10^{20}	−0.86	−1.04	0.07	1
0112+03	2.42	1.0×10^{21}	−1.0	−0.9	$< 2 \times 10^{-5}$	1,5
1223+17	2.47	3.0×10^{21}	−1.5	−0.6	$< 9 \times 10^{-7}$	1,5
1337+11	2.79	8.0×10^{20}	< -1.0	?	$< 1.3 \times 10^{-4}$	5,9
0528−25	2.81	2.0×10^{21}	−0.76	−0.47	5×10^{-5}	10,11
1946+76	2.84	2.0×10^{20}	−2.5	?	$< 9 \times 10^{-6}$	1,6
0000−26	3.39	2.0×10^{21}	< -1.9	< -0.3	$< 3 \times 10^{-6}$	5,12

[a] Upper limits based on T_{ex} = 1000 K, b = 5 km s^{-1}.
REFERENCES: 1 - Ge & Bechtold 1999; 2 - Meyer et al. 1992; 3 - Steidel et al. 1995; 4 - Meyer et al. 1995; 5 - Pettini et al. 1994; 6 - Lu et al. 1995 7 - Wolfe et al. 1994; 8 - Black et al. 1987; 9 - Lanzetta et al. 1989; 10 - Sriannand & Petitjean 1998; 11 - Lu et al. 1996; 12 - Levshakov et al. 1992.

High resolution spectroscopy of the H_2 lines give estimates of excitation temperatures, volume densities (assuming some of the excitation is collisional), and the ultraviolet radiation field which can excite or photodissociate the molecules. Details of these quantities for the quasar absorbers with detected H_2 are given in Sriannand & Petijean (1998) and GBK. Here we discuss the quantity β_0, which is the photodissociation rate of molecules in the Lyman and Werner bands. The local solar neighborhood value is $\beta_0 = 5 \times 10^{-10}\ s^{-1}$ (Jura 1975ab; Savage et al. 1977). Note that the metagalactic H I ionizing radiation field, which determines the ionization of the Ly-α forest (Bechtold 1994), is irrelevant: for $J_\nu(912\ \AA)$ = -21, $\beta_0 = 2 \times 10^{-12}\ s^{-1}$ (Sriannand and Petitjean 1998).

In the case of Q 0528-25, the absorber redshift is close to the quasar redshift, and the radiation field is very high, possibly due to proximity to the quasar: $\beta_0 = 3 \times 10^{-7}\ s^{-1}$. In both cases where the absorber is intervening, the inferred value of β_0 is also high: for q0013-004, $\beta_0 = 6.7 \times 10^{-9}\ s^{-1}$ (Ge & Bechtold 1999), and for q1232+0815, $\beta_0 = 7 \times 10^{-9}\ s^{-1}$ (GBK). These last results must be regarded with caution, however, since they are based on moderate resolution data, and β_0 would be systematically *overestimated* if, for example, more than one velocity component is present. If confirmed with high resolution spectra, however, these high values of β_0 compared to the solar neighborhood values suggest that star-formation rates are higher in PGFs at z$\sim$2 than in the present-day Milky Way.

3. Future Prospects

Although all known damped Ly-α absorbers appear to be enriched with heavy elements (Pettini et al. 1999 and references therein), as are the quasars used to find them

(Ferland et al. 1996, Hamann 1999), someday one may be able to find UV bright objects at high enough redshift to probe truly primordial H_2. The chemistry of primordial molecule formation is important for models of the thermal history of the early intergalactic medium since H_2 cooling controls the collapse and fragmentation of the first PGFs. Observations of primordial H_2 would allow interesting measures of the ultraviolet radiation background, which may suppress the formation of low-mass objects (Couchman & Rees 1986; Efstathiou 1992; Haiman, Rees & Loeb 1996).

In the shorter term, we note that to date, the observations of H_2 in damped Ly-α absorbers from the ground have been carried out on 4m-class telescopes which can only reach the brightest, and least reddened objects. With 8m class telescopes, higher dispersion spectra can be obtained of the Lyman and Werner bands, as well as the weaker vibrationally excited H_2 transitions which suffer less from saturation and blending with the Ly-α forest (e.g. Federman et al. 1995). Future very large telescopes, currently being planned, will be able to observe fainter objects, and probe heavily extincted and truly molecular lines-of-sight. The reddened background quasars may be found in all sky surveys in the near-IR and radio, currently underway.

The recent launch of FUSE and the installation of STIS on HST will greatly extend the observations of H_2 in local galaxies and low redshift quasar absorbers. As this review was written, observations were underway with these instruments, but results were not yet available. Spectra of a few lines-of-sight in the LMC and SMC observed with Orpheus II suggest that future observations will provide a rich source of information on H_2 in the interstellar medium in nearby galaxies (Richter et al. 1998, de Boer et al. 1998).

Future missions being studied by NASA, particularly SUVO, a large ultroviolet-optimized telescope with an echelle spectrometer (see Shull 1999), would be ideal for detailed studies of molecular hydrogen in quasar absorbers.

I am indebted to Jian Ge and John H. Black, long time collaborators on this work, for their contributions. I am grateful for encouragement from D. Meyer and A. Stopeck. Support was provided by NSF grant AST-9617060. Observations reported in this paper were obtained at the Multiple Mirror Telescope Observatory, a facility operated jointly by the University of Arizona and the Smithsonian Institution. Support for this work was provided by NASA through grant number AR-05785.01-94A from STScI, which is operated by AURA, Inc., under NASA contract NAS 5-26555.

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