QUASAR ROTATION MEASURES AND OPTICAL ABSORPTION SPECTRA — WHAT CAN WE LEARN ABOUT COSMIC MAGNETIC FIELDS ?

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ABSTRACT. This paper reviews early attempts to deduce important constraints on the magnetic fields of high-redshift objects through a study of the rotation measure (RM) of QSOs. We have combined detailed studies of RM and optical spectra of 48 QSOs and have statistically analysed RM data on 116 objects and conclude that the objects which give rise to QSO metal-line absorption are also responsible for the observed extragalactic component of RM. This allows us to estimate their average magneto-ionic properties.

1. Introduction

The measured RM of extragalactic sources is the sum of contributions from the Galaxy and all extragalactic magneto-ionized gas lying along the line-of-sight. Intervening galaxies or galactic halos, protogalaxies, intergalactic clouds, intracluster gas, a widespread coexpanding diffuse intergalactic medium, material associated with the QSO itself – or a combination of these – can all contribute. In order to determine which of these dominate the QSO extragalactic or *residual* rotation measure (RRM) we have used a two methods: comparison to detailed optical spectra, and comparison of the statistical distribution of RRM and to independently determined properties of astrophysical objects. We conclude that the objects which give rise to QSO metal-line absorption are most probably responsible for the observed excess RRM's. The importance of this result lies in the potential for examining magnetic fields in individual galaxies, clusters, or their progenitors out to redshifts of about 3. Other methods, whilst essential in elucidating the structure of magnetic fields in our own and in nearby ordinary galaxies, are limited to the study of low redshift objects.

Kronberg and Simard-Normandin (1976) found that both a quasar-intrinsic RM and that due to a widespread coexpanding IGM are small. The former follows because low redshift QSOs have a small variance in their RRM and the latter because a substantial fraction of high redshift QSOs also have small RRMs. This suggests that QSO RRM arises in discrete intervening systems, rather than in a widespread magnetized IGM. These results were subsequently confirmed by Welter, Perry and Kronberg (1984, hereafter WPK).

An important signature of intervening systems is absorption lines in the spectra of background QSOs. These arise only when the column density within a limited velocity interval is high enough. In principle, objects can have a strong RM without accompaning optical absorption or vice-versa. For example, gas which is fully ionized and has a moderate magnetic field may show little optical absorption but strong RM. However, the column density required for detectable absorption is similar to that for detectable RM and so correlation at some level would be expected. Another important constraint on optical detectability is that the line must be redshifted into an observable window. This

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important effect will be discussed later.

There are three classes of absorption-line systems present in QSO spectra. The vast majority — the "Ly-α forest" — are hydrogen Lyman-α absorption lines (on average about 60 lines per unit redshift) and are thought to correspond to tenuous intergalactic clouds containing only hydrogen and helium. Secondly, and less frequently, there are heavy element lines, mainly ionized carbon, silicon and magnesium. These are thought to originate from extended halos, discs or gas clouds associated with galaxies. Finally, broad absorption line troughs are seen in about 10% of QSOs and are believed to be produced by material associated with the QSO itself. For a more detailed review of QSO absorption-line systems see, for example, Sargent (1986).

Two essentially distinct methods have been used to analyse possible correlations between QSO absorption-line systems and RRMs: that of Kronberg and Perry (1982, hereafter KP) and of WPK. KP's and WKP's methods ought not to be seen in isolation: they provide complementary approaches to different aspects of the same problem, and it was in this spirit that we recently analysed new data. We (Watson and Perry, 1989, hereafter WP) used an analysis based on WPK's in our reconsideration of the 'Ly-α forest'; for metal-line systems we applied variations and developments of KP's methods. Simard-Normandin, Kronberg and Button's 1981 measurment of the RM of 555 sources is the basic data for most of the analysis.

KP's method searches for correlations between the presence of strong absorption and large RRMs. This is achieved by dividing the sample into two subsamples, denoted 'strong' and 'weak', according to the strength of metal-line absorption and comparing their RRMs. This has the appealing property of being a very direct method of investigation. It does, however, suffer seriously from several practical problems discussed below. The most important of these is a lack of suitable data: relatively few radio-loud QSOs have both well determined RRMs and high-quality optical data.

WPK developed an entirely different approach which overcomes most of the problems of the KP analysis but introduces a set of its own. They postulate a source of QSO RRM (such as the QSO itself, or a certain class of absorption-line systems) and use the distribution of RRM to constrain the magneto-ionic properties of that population. Any inconsistency with properties determined by other independent means clearly rule out the proposed source as the origin of QSO RRM.

This method removes the necessity of having both good radio and optical data on each object: it merely requires a large set of well-determined RRMs and independent knowledge of the properties of the proposed sources. Regrettably we know little about the magneto-ionic properties of many of the objects (such as galaxies or clusters) which could be responsible for the excess RRMs — indeed their elucidation is the motivation of this research. Secondly, and as importantly, the method suffers an intrinsic limitation: it can rule out potential sources of RRM but can not positively discriminate amongst sources which are consistent with the data.

2. Lyman-α Forest Clouds

KP gave evidence that the Ly-α clouds observed in QS0 spectra were not the originators of QSO RRMs. Recent advances in the knowledge of their physical properties and distribution (Sargent, Young, Boksenberg and Tytler, 1980; Foltz *et al.*, 1984; Carswell *et al.*, 1982; Murdoch *et al.*, 1986; and Tytler, 1987) makes a more detailed analysis in the spirit of WPK possible. By careful examination of their physical properties and cosmological distribution, WP determined what magnetic field strength in the clouds would be required if they were to produce the observed RRM. WP find that the average electron density-weighted, line-of-sight component of the magnetic fields in the clouds must be at least twelve times the equipartition valueto account for the observed RRM.

Clearly, the requirement for such an absurdly high magnetic field allows us to disqualify Ly-α clouds as originators of RRM, unless other evidence comes to light suggesting that they indeed have pronounced magnetic fields or new data dramatically revises their physical properties. It is possible that the peculiar "pancake" clouds suggested by Barcons and Fabian (1986) may be found to have such large magnetic fields but, in the standard picture, Ly-α clouds are conclusively excluded.

3. Statistical Analysis of RRM Alone

WPK analysed the RRMs of 116 QSOs (for which optical spectra were mostly not available). They considered models in which the RRM arose (i) within the QSO itself; (ii) in a population of discrete objects along the line-of-sight; and, finally, (iii) in which both the QSO itself and a population of intervening rotators contributed to RRM. (This last model was restricted to the case in which the RM properties of the QSO and of the intervenors were similar, as might occur if the QSO was itself located in a typical member of the intervenor population, e.g. a galaxy.).

Their statistical analysis found that all the models were consistent with the data. However, they found that intervening rotators, either alone or with a contribution from the QSO itself, gave the best fit to the data. These conclusions were in agreement with KP's earlier result. As candidates for the intervenors they suggested galactic halos and clouds of intracluster or intragroup gas, and they estimated that magnetic fields in such clouds are about 2 —10 μG, with cell sizes $\approx$ 45 kpc.

4. Direct Comparison Of Metal-Line Absorption And RRM

4.1 KP'S ORIGINAL ANALYSIS

KP analysed a sample of 37 QSOs for which both accurate RRMs and good absorption line data were available. They demonstrated a correlation between high RRM and the presence of strong metal-line absorption. (However, as discussed below, it was impossible to be sure that all intervenors had been detected.) They noted that it was consistent to interpret both the RRM and the metal-line absorption as arising predominantly in the halos or discs of galaxies. On the basis of this interpretation, KP estimated — or put limits to — the magnitude of the magnetic field in certain of the observed metal-line systems; these estimates were usually a few tens of μG, or less.

KP noted the uncertainties concomitant with the small size of their sample, but the dearth of sufficiently high resolution and large redshift-window optical spectra for QSOs, at that time, prevented them from drawing firmer conclusions.

A second major problem in their method, and one which we have since been able largely to eliminate in our analysis, is the difficulty of isolating those QSOs with strong absorption from a general population without unwittingly selecting QSOs having other properties (such as redshift, magnitude, spectral index) significantly different from the population as a whole.

One final problem stems from the limitations in optical spectral coverage. These define limits to the redshift range over which a given line can be detected, and determine the sections of the line-of-sight in which absorption-line systems could or could not have been detected. It is almost inevitable that some such systems will be missed and that there are gaps in our knowledge of intervening systems in individual QSOs. Some QSOs will be incorrectly classified as 'weak' because any systems within the gaps will not be observed. (An example in point in 3C309.1 - see KP).

4.2 KP REVISITED

WP recently expanded and revised KP's list of absorption line spectra, obtaining 48 objects which break down conveniently into subsamples of 24 'weak' and 24 'strong' absorption QSOs.

By integrating the known distribution of absorption systems (Kunth, 1987) over the gaps in spectral coverage, we calculated the number of systems expected to have been missed in the spectra of 'weak' QSOs in order to quantify the bias introduced by applying KP's method to our data. We expect twice as many absorption systems have been missed from the 'weak' quasars as from the 'strong' ones, despite the 'weak' quasars being at significantly lower redshifts. We thus expect that some of the quasars classified as 'weak' have undetected intervening absorption systems, which will blur the distinctions between the samples in a straightforward application of KP's method.

It is important to note that *this systematic effect does not bias our tests in favour of our final conclusion*, rather it works in the opposite direction. Any accidental mixing of the data makes differences harder to find, and thus more significant when actually detected.

We have partially countered the lack of coverage at low redshift by examining Schmidt plates for visible, low-redshift galaxies near to the line of sight to the QSO, but we stress that the mid-redshift gaps (between MgII and CIV coverage) in the data cannot be eliminated using ground-based telescopes. Only with the use of space telescopes, such as the HST, will this problem be resolved. It must also be stressed that merely observing larger or more homogeneous samples will *not* talleviate this limitation — it is intrinsic to ground-based observations.

The 'weak' and 'strong' subsamples are not evenly distributed and effectively sample different ranges of redshift, with those QSOs possessing strong absorption tending to occur at higher redshifts than those with weak absorption. If the source of the RRM is intrinsic to the QSOs and evolves as suggested by WPK, then the observed systematic difference of RRM between the two samples could be due to their differences in redshift. Furthermore, the lines-of-sight to the 'strong' QSOs sample a population of absorbers of higher average redshift than the 'weak' QSOs. Were there to be significant differences in the magneto-ionic properties of the population of absorbers at different redshifts – and indeed there is evidence that significant changes in related properties (*eg*. ionization ratios, equivalent widths, space density) do occur – this could further complicate KP-like tests.

Thus, using KP-like tests alone, it is impossible to distinguish whether the excess RRM is due to intervening metal-line absorption systems, or is due to some evolving intrinsic property of the QSO.

A possible correlation of RRM to redshift was investigated by constructing two new subsamples of 'high' and 'low' redshift objects, ignoring absorption classification entirely. Appropriately pairing the sources and comparing the magnitudes of the emission-redshift corrected RRMs leads, at a confidence level of greater than 99%, to the rejection of the hypothesis that both the 'high' and 'low' subsamples are drawn from the same population, in favour of the 'high' redshift QSOs having a greater median magnitude of corrected RRM.

4.3 A NEW APPROACH

A more powerful test was clearly needed. To this end, the data were ordered by ascending z_e and the closest of 'weak'-'strong' pairs were selected to form a new sample. This procedure yielded only 8 pairs, spanning $0.8 \leq z_e \leq 2.4$, with an r.m.s. separation in redshift of only 0.038. Clearly, any redshift evolution of an intrinsic source of RRM ought to be filtered out within each pair. Non-parametric tests (such as the Mann-Whitney U-test used by KP) are the safest in situations where little is known of the nature of an effect. Regrettably, such tests waste independent knowledge of the distributions involved, which is highly undesirable with our perilously small sample.

We constructed a non-standard test, in which the RRM was normally distributed about zero with equal variances *within* each 'weak'-'strong' pair. Larger samples (such as that considered by WPK) and the general random walk nature of RM lead us to believe that a normal distribution is a good approximation. Suggestions by Rudnick and Jones (1983) and Wrobel (1987) that there may be a wavelength dependent structure to the nucleus of at least certain QSOs (which might lead to a bimodal distribution of RRMs) do not counsel strongly against a normal distribution, as their wavelength dependent structure would occur on smaller scales than our effective beam width.

To test this hypothesis we used a Monte-Carlo method and concluded, at a confidence level of greater than 99%, that the variances of the RRMs of the weak and strong absorption QSOs in our sample are not the same, and that the variances of the strong QSOs are significantly greater than those of the weak. We consider that this test does not suffer from the problems of selection inherent in our earlier tests and that any uncertainty introduced by incomplete knowledge of absorption will bias against our conclusion, rather than towards it. This test is the strongest and safest discriminator we have between an intrinsic or absorption related origin of QSO RRM and it decides in favour of the metal-line systems as the principle origin of QSO RRMs, reinforcing KP's and WPK's conclusions.

5. Discussion

Our work has firmly established that metal-line absorption systems produce the majority of the extragalactic RM of QSOs. This gives us a tool for probing the magneto-ionic properties of condensed objects at redshifts up to about 3.

We have estimated the likely present epoch properties of the metal-line systems (galaxies and groups or clusters) to be $B \approx 2\mu\mathrm{G}$, $l \approx 45$ kpc, $n_e \approx 10^{-3}\mathrm{cm}^{-3}$. However, the systems undergo evolution with the intrinsic cloud RM increasing roughly like $(1+z)$.

It is important to have coordinated observations of QSOs in both the optical and radio in order to improve the size of our sample and establish electron column densities, sizes and temperatures. Our results suggest that such data will help to further elucidate the nature of magnetic fields in galaxy systems out to $z \approx 3$. Such observations are now planned.

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