THE UNUSUAL QUasar PG 1407+265

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ABSTRACT

PG 1407+265, discovered in the Palomar-Green Survey (Schmidt & Green 1983), was identified as a z ~ 1 radio-quiet quasar on the basis of a single weak line. Further observations over a wide wavelength range confirm the identification but reveal the object to have unusual emission-line properties. Broad Hz is the only strong emission line with Hβ and Lyman-α almost undetectably weak. The emission lines show a range in redshift of over 10,000 km s⁻¹, systematically decreasing with ionization potential or, almost equivalently, increasing to longer wavelengths. A value of z = 0.94 ± 0.02 is a reasonable statement of our knowledge of the quasar’s redshift. However, the object’s continuum properties are those of a normal radio-quiet quasar. We discuss a number of possible models for the object, but its nature remains puzzling.

Subject heading: quasars: individual (PG 1407+265)

1. INTRODUCTION

In the course of our survey of quasar continuum energy distributions (Elvis et al. 1994), we realized that the redshift of one of our sample objects, PG 1407+265, was not secure. The assignment of z = 0.944 by Schmidt & Green (1983) was based on a single extremely weak line identified as Mg II λ2798. Noisy IUE spectra obtained in 1983 and 1987 did not reveal any further lines. Confidence in the identification was increased with the publication of a high-quality optical by Steidel & Sargent (1991) which showed weak Fe II emission in addition to the Mg II line, but a 1989 IUE spectrum of improved quality by P. O’Brien failed to show any evidence for hydrogen Lyman-α.

We have carried out a comprehensive multiband study (Table 1) of this object as part of our larger survey of quasar properties (Elvis et al. 1994). Our optical spectrophotometry showed no evidence for significant variability over a baseline of 10 yr; this, the lack of polarization (Berriman et al. 1990), and the radio-quiet nature of the source make it unlikely that it is related to BL Lac objects. The X-ray flux detected by the Einstein and ROSAT satellites is at the level expected for a quasar, and the continuum shape is normal with an ultraviolet bump of median strength and, as expected, an inflection at between 1 and 2 μm in the putative rest frame. Nevertheless, the equivalent width of Lyman-α (~ 8 Å) is extremely low compared to those of other objects (20–80 Å; Francis et al. 1991).

2. OBSERVATIONS

2.1. Optical Spectrophotometry

We obtained optical spectrophotometry of the quasar during 1988 at the Multiple Mirror Telescope (MMT) using the Blue Channel and the Faint Object Grating Spectrograph (FOGS). Higher resolution data were obtained through a 1" slit, and the flux level was normalized using lower resolution data through a 5" slit. Mg II and C III emission lines are detected, together with strong Fe II emission. In an attempt to observe the region around rest frame Hβ, I. W. Browne, P. N. Wilkinson, and D. Henstock kindly obtained Faint Object Spectrograph (FOS) data on the 2.5 m Isaac Newton Telescope (INT) extending to 10000 Å. Unfortunately the spectral region in question sits on atmospheric absorption lines, but the presence of an Hβ line of normal strength can be ruled out. The normalization of all the spectra is in good agreement with CCD photometry obtained at the 0.6 m telescope of the F. L. Whipple Observatory in 1986. The combined optical spectrum is presented in Figure 1.

2.2. Ultraviolet Observations

The IUE spectra were retrieved from the National Space Science Data Center and analysed using the RDAF IDL package. The spectra were extracted and calibrated using the standard GEX Gaussian Extraction algorithm (Urry & Reichart 1988). HST data, taken as part of the Absorption Line Key Project (Babcock et al. 1993), were retrieved from the Hubble Data Archive using Starview and analyzed with the STSDAS package. We adjusted the flux of the G160L observation, taken through the 0.1 aperture, to match the data in the other gratings, taken through the 0.25 × 0.20 slit. We note that the G270H spectrum was not analyzed by Babcock et al. because it covers wavelengths longward of Lyman-α. Weak O IV + Si IV and C IV lines are present in the HST spectrum (Fig. 2) and (less obviously) in the IUE data. The Lyman-α line is present but cut up with superposed absorption lines. Our value of 8 Å for the equivalent width of this line is approximate and based on an ad hoc linear continuum fit at 1300 Å and 1140 Å (Table 2). The HST data agree well in flux (to within 15%) with the 1989 and 1986 IUE data; the quasar’s far-ultraviolet flux seems to have increased by 30% since the 1983 IUE observation. This degree of variability is normal in quasars (Kinney et al. 1991).

2.3. Infrared Observations

Infrared spectroscopy was obtained through a service observation carried out on UKIRT (the United Kingdom...
Infrared Telescope). The spectrum shown in Figure 3, which shows a strong Hz line at an observed wavelength of 1.28 μm, was obtained on 1994 January 29 with the cooled grating spectrometer CGS4, using the 150 mm camera and a 75 line mm⁻¹ grating in second order, resulting in a spectral resolution corresponding to 780 km s⁻¹. One resolution element is approximately equal to 1 detector pixel; however, the detector was stepped in increments of one-third of a pixel to improve sampling. The slit width used was 3", roughly equal to 1 original detector pixel. Standard nodding, calibration, and atmospheric correction techniques were followed. Because of the large slit size, the wavelength calibration could potentially be offset if the object was not properly centered; any such error is certainly less than 400 km s⁻¹, and is probably much less.

JHKL photometry was obtained at the MMT in 1988 and shows the continuum inflection characteristic of a quasar. Examination of the IRAS sky images shows that PG 1407+265 is 3' from the strong 60 μm source IRAS 14070+2636, which has been identified with the starburst galaxy Haro 40. Addscans of the IRAS survey data show no evidence for a 60 μm detection of the quasar, but we have reported a formal, marginal 25 μm detection (Elvis et al. 1994), although this should probably be treated with skepticism because it was not detected in any other IRAS band.

![Spectrum of PG 1407+265](image.png)

**Fig. 1.**—Optical spectrum of PG 1407+265. The plot shows the combined observations from the MMT Blue Channel and FOGS instruments and the INT. Expected positions of emission lines and selected Fe II multiplets are indicated. The Blue Channel and INT data have been multiplied by a constant 12% factor to agree with the FOGS data.
2.4. X-Ray Observations

PG 1407 + 265 was observed on 1992 January 19 with the ROSAT PSPC (Trümer 1983; Pfeffermann et al. 1987) for 3229 s. The source is well detected and is consistent with the point-spread function. We note that there is no evidence for any significant confusing source at the position of Haro 40 (Green et al. 1989) with a 3σ upper limit of $1 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ (0.4–2.4 keV).

We extracted counts from a 3' circle around the position of PG 1407 + 265, together with background in an annulus from 3.5 to 7', using the IRAF/PROS package. The data were analyzed with the XSPEC spectral fitting package using the 1993 January (DRM 36) response matrix. We fitted a single power-law spectrum with Galactic absorption (Morrison & McCammon 1983). The data are consistent with this model, and the fitted absorption was consistent with the Galactic value of $1.38 \pm 0.10 \times 10^{20}$ cm$^{-2}$ (Elvis, Lockman, & Wilkes 1989), so we repeated the fit with absorption fixed at this value. The best fit gave a power-law energy index of 1.61 ± 0.05 and a 1 keV flux of $1.0 \pm 0.04$ μJy, with a reduced χ$^2$ of 0.49 (Fig. 4). Consistent results were obtained using the SPECTRAL package in IRAF/PROS. We also set an upper limit to the amount of extra absorption (above Galactic) due to cold material at the redshift of the source of $N_{\text{H}} < 3.1 \times 10^{20}$ cm$^{-2}$ (or $4.9 \times 10^{19}$ cm$^{-2}$ for extra absorbers at zero redshift); although there are no obvious edges in the spectrum, we cannot rule out the presence of an ionized absorber. Our derived power-law index is steeper than, but consistent with, the Einstein IPC result of $1.2 \pm 0.2$ (Wilkes & Elvis 1987); note that fits to PSPC data appear systematically steeper than the

### Table 2

<table>
<thead>
<tr>
<th>Line</th>
<th>Instrument</th>
<th>$\lambda_{\text{obs}}$</th>
<th>Redshift</th>
<th>EW (Å)</th>
<th>Luminosity ($10^{44}$ ergs s$^{-1}$)</th>
<th>Typical EW* (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lyα $\lambda$2125</td>
<td>IUE</td>
<td>...</td>
<td>...</td>
<td>$&lt;10$</td>
<td>30–100</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>HST</td>
<td>2370</td>
<td>0.95 ± 0.015</td>
<td>8 ± 3</td>
<td>10:</td>
<td>...</td>
</tr>
<tr>
<td>O iv] + Si iv $\lambda$1400</td>
<td>IUE</td>
<td>2690</td>
<td>0.92 ± 0.01</td>
<td>9.1 ± 3</td>
<td>4.2</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>HST</td>
<td>2675</td>
<td>0.912 ± 0.004</td>
<td>4.3 ± 2</td>
<td>2.2</td>
<td>...</td>
</tr>
<tr>
<td>C iv $\lambda$1549</td>
<td>IUE</td>
<td>2960</td>
<td>0.911 ± 0.01</td>
<td>3.6 ± 2.5</td>
<td>1.5</td>
<td>20–50</td>
</tr>
<tr>
<td></td>
<td>HST</td>
<td>2980</td>
<td>0.924 ± 0.004</td>
<td>4.6 ± 2</td>
<td>1.9</td>
<td>...</td>
</tr>
<tr>
<td>C m[ + Al m $\lambda$1909, 1858</td>
<td>MMT/Blue</td>
<td>3700</td>
<td>0.94 ± 0.03</td>
<td>9.9</td>
<td>3.5</td>
<td>...</td>
</tr>
<tr>
<td>Mg II $\lambda$2798</td>
<td>MMT/Blue</td>
<td>5435</td>
<td>0.94 ± 0.003</td>
<td>23.5</td>
<td>4.6</td>
<td>50–80</td>
</tr>
<tr>
<td></td>
<td>MMT/FOGS</td>
<td>5450</td>
<td>0.948 ± 0.0012</td>
<td>23.2</td>
<td>4.8</td>
<td>...</td>
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<tr>
<td></td>
<td>INT</td>
<td>5445</td>
<td>0.946 ± 0.002</td>
<td>11.6</td>
<td>2.2</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>SS91b</td>
<td>...</td>
<td>0.947</td>
<td>24.4</td>
<td>...</td>
<td>...</td>
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<tr>
<td>Hβ $\lambda$4861</td>
<td>INT</td>
<td>...</td>
<td>...</td>
<td>$&lt;0.40$</td>
<td>$&lt;2.2$</td>
<td>...</td>
</tr>
<tr>
<td>Hα $\lambda$6563</td>
<td>UKIRT</td>
<td>12850</td>
<td>0.958 ± 0.001</td>
<td>126.0</td>
<td>4.1</td>
<td>250–1200</td>
</tr>
</tbody>
</table>


IPC (Fiore et al. 1994). The normalization, however, is more than twice as high as the IPC value of 0.44 $\mu$Jy, indicating significant X-ray variability over a timescale of a decade.

3. RESULTS

3.1. The Redshift of PG 1407 + 265

The initial published redshift estimate (Schmidt & Green 1983) was based on the single Mg ii line. The failure to detect other lines in our intermediate signal-to-noise ratio spectrophotometry and in the IUE data raised the possibility that alternate (even nonquasar) identifications might be possible (Elvis et al. 1994).

Our observation of the strong H$\alpha$ line in the near-infrared and our identification of the weak C iv and O iv + Si iv lines in the HST data provide conclusive evidence that the redshift of the object is indeed near unity. The high-quality spectrum of Steidel & Sargent (1991) claimed to confirm the redshift as $z = 0.947$ and identified emission redward of Mg ii as due to the $\lambda 2950$ Fe ii feature. However, the feature they claimed as C iii] (observed wavelength 4019.4 Å; their Table 1) is incon-

![Graph](image)

**Fig. 3.** Infrared spectrum of PG 1407 + 265, obtained as a UKIRT service observation on 1994 January 29.

![Graph](image)

**Fig. 4.** ROSAT PSPC pulse-height spectrum of PG 1407 + 265. The upper panel shows the extracted counts (crosses) and the fitted power-law model (solid line), while the lower panel shows the ratio of the counts to the model in each channel. The power-law model includes Galactic absorption of $1.38 \times 10^{20}$ cm$^{-2}$.
sistent with this redshift; this feature corresponds to a weak unidentified line in the composite spectrum of Francis et al. (1991) and is not as strong in our MMT data. The true C \text{III}] + Al \text{II} feature is the weaker one visible in their spectrum at approximately the correct rest wavelength.

The wavelengths of the peaks of each emission line were measured and used to derive redshift estimates (Table 2). We quote nominal “1\%” uncertainties which are one-third of our eyeball estimates of the maximum uncertainty in the peak location. As is typical for quasars, the redshifts of the low-ionization lines are larger than those of the high-ionization lines (Gaskell 1982; Wilkes 1984; Espey et al. 1989). However, the range in redshift for PG 1407+265 is an order of magnitude larger than typically seen: 10200 ± 1200 km s^{-1} between H\alpha and C IV compared with ∼1000 km s^{-1} in the earlier studies. The wavelength scales of the various instruments should be much better than this; the optical spectra were taken with the slit vertical to avoid refraction effects, although this is not an issue for the ultraviolet spectra, and refraction is small enough in the infrared to compensate for the larger slit width. Uncertainties in the velocity scale due to slit width and refraction effects should be less than 500 km s^{-1} in all cases.

Figure 5 shows the various emission lines on a common velocity scale with zero point set by Mg \text{II}. We see a significant trend of the velocity shift to increase with the ionization potential of the emission line (Fig. 6a). We note that a trend with rest wavelength is almost equivalent (Fig. 6b). We suggest that = 0.94 ± 0.02 is a reasonable statement of our knowledge of the quasar's redshift. Note in Figure 5 that there is a narrow absorption feature in Lyman-\alpha coincident with the velocity of the H\alpha emission line, implying some overlaid neutral hydrogen component.

We also measured approximate line widths and fluxes. C IV \lambda 1549 and the broad component of H\alpha both have full width at half-maximum (FWHM) around 7000 km s^{-1}. Mg \text{II} has a similar component but with a broad red-wing “shelf” of blended Fe \text{II} UV multiplets leading to a formal FWHM of around 12,000 km s^{-1}. C \text{III}] \lambda 1909 appears to be equal in flux with Al \text{II} \lambda 1858, although our spectrum has a low-signal-to-noise ratio in this region.

3.2. Line Properties

The emission lines in PG 1407+265 appear unusually weak when viewed by eye. How extreme are these equivalent widths? Table 2 gives the details of our measured values, including estimates of the integrated rest frame luminosity in each line. Typical emission-line properties of quasars are given in Table 12.4 of Osterbrock (1989) and for a subset of lines in Francis et al. (1991). While the Osterbrock data are not based on any specific sample, the latter paper gives average properties of the well-defined Large Bright Quasar Survey. Further, Francis (1993) gives histograms of equivalent width for the bright ultraviolet lines which may be used to measure how unusual PG 1407+265 actually is, although their spectral signal-to-noise ratio is too low to give reliable measurements for individual objects at the low equivalent widths we are probing.

The O IV] equivalent width, W(O IV]), is relatively normal in PG 1407+265, only a factor of 2 low. However, W(Ly\alpha) is in the bottom 3% of the Francis et al. distribution (typical values 30–100 Å), as is the C IV strength (typically 20–50 Å), while W(Mg II) is in the lowest 4% of its corresponding distribution (typical values 50–80 Å). Quasar H\alpha equivalent widths are still hard to find, with results from several groups (Baker et al. 1994; Baker 1994) indicating that typical values are in the range 250–1200 Å, consistent with the early data of Baldwin (1975). However, we note that three objects in the sample of Espey et al. (1989) have values between 140 and 150 Å, comparable to our value of W(H\alpha) = 126 Å. We may summarize by saying that most of the line ratios in PG 1407+265 are not exceptional within the large uncertainties, but the equivalent widths for the principal lines are anomalously weak by factors of 3–10. In contrast, the Fe II multiplets (both optical and UV) appear to be unusually strong.

3.3. Continuum Properties

In contrast to the lines, the continuum properties of PG 1407+265 are remarkably normal. We present the dered-
like continuum component which may reduce the strength of the emission lines in some flat-spectrum radio quasars.

4. DISCUSSION

The emission-line spectrum of PG 1407+265 is unlike that of any other radio-quiet quasar we have seen, e.g., of ~100 in Elvis et al. (1994), Kinney et al. (1991), and Boroson & Green (1993). In Figure 8, we contrast the 1000–8000 Å rest frame spectrum of PG 1407+265 with comparable data for the ordinary, low-redshift quasar PG 1211+143. The difference in the amount of energy in the ultraviolet lines is dramatic. We now consider several possible explanations for the weak lines and differential redshifts of PG 1407+265.

1. Not a quasar.—Prior to the detection of Hα, we had speculated that the object might not be a quasar at all. That line and the overall multiwavelength continuum properties rule out that possibility.

2. A beamed continuum.—The lines are washed out by a beamed, nonthermal component (a jet along the line of sight). This solution, which would be unprecedented in a radio-quiet object, is ruled out by the lack of continuum variability and the normal shape of the energy distribution.

3. Low BELR covering factor.—The broad emission line region (BELR) has a lower covering factor, intercepting less of the continuum radiation. This simple explanation accounts for the low equivalent widths of the emission lines which originally drew our attention to the object but does not address the bizarre C IV and O IV line shifts.

4. Abnormal photoionizing continuum.—The weakness of the lines is intrinsic and due to an abnormal photoionizing continuum as seen by the line-emitting region. Although the continuum we see is normal, we may be looking at a special angle. If there is obscuration between the central source and most of the BELR (except along our line of sight), this might occur, although we have not tried to reproduce the observed spectrum with a photoionization code. Since objects like PG 1407+265 are clearly rare (a few percent at most), explanations involving special geometry are reasonable.

5. Time lags.—The UV continuum has recently brightened, and the lines have not yet caught up. The lack of optical and UV variability on a 10 yr timescale casts doubt on this, although the factor of 2 increase in the X-ray since 1981 is worth noting. This explanation would imply an effective BELR radius large compared with 10 lt-yr, while scaling with the expected $L_\nu^{1/2}$ dependence from NGC 5548 (Clavel et al. 1991) would predict a much smaller BELR radius, ~1 lt-yr.

6. Abnormal BELR physical properties.—The weakness of the lines is intrinsic and due to abnormal cloud properties in the broad emission line region. Before the detection of Hα, the possibility of "hydrogen-depleted" clouds was tenable (if physically unlikely). The presence of Hα requires some other peculiarity: the size or density of the clouds may be unusual, or the distance of the BELR gas from the central object may be abnormal, leading to an unusual ionization parameter.

7. Fe II-dominated continuum.—The emission lines have a normal equivalent width with respect to the true continuum but are masked by strong Fe II emission as in IRAS 07598+6508 (Lawrence et al. 1988). This might work for some of the optical lines but cannot contribute to the weakness of C IV and Lyman-α.

8. Dust absorption.—The weakness of the short-wavelength lines is due to patchy reddening between us and the quasar.
nucleus. This is unlikely since the continuum source shows no evidence of reddening: the ultraviolet continuum is strong, and the soft X-rays show no significant absorption in excess of Galactic. The absence of a definite IRAS detection implies (Fig. 6) that the object is not exceptionally far-infrared bright, unlike some of the Fe II emitters studied by Lawrence et al. (1988), and so most of the continuum cannot be reprocessed by dust. Any explanation based on reddening must therefore explain how the lines but not the continuum are affected.

9. Line absorption.——PG 1407 + 265 is a weak BAL quasar in which the absorption lines are eating away at the emission. Note that the Lyman-α region (Fig. 3) appears to contain narrow absorption lines, although there is no evidence for any Lyman-continuum break, so $N_\text{H} \leq 10^{17}$ cm$^{-2}$. Patchy absorption leaves the continuum source unaffected, while most of the BELR emission is soaked up in a broad absorption line (BAL) region lying between us and the high-ionization region of the BELR generating C IV and O IV]. This explanation can address the observed redshift differences. The velocity of the BAL clouds is such that the red wing and center of the BELR lines are preferentially absorbed. The remaining blue wing gives an artificially low redshift. The low-ionization emission lines, which are generated farther from the nucleus, suffer less or no red BAL absorption and give the true emission redshift, which is nearer to $z = 0.95$. The problem with this picture, as with dust absorption, is the low probability that the bulk of the emission lines would be absorbed without affecting the continuum source.

10. Gravitational amplification.——The equivalent widths are low because the continuum source is magnified by a stellar mass microlens along the line of sight. Dalcanton et al. (1994) set probabilities on the cosmological density of lensing objects based on the absence of weak equivalent width objects in some quasar samples; to cast their argument slightly differently, if microlensing has any significant effect on the quasar population, we should expect it to show up in a few high-luminosity, bright objects with weak equivalent widths. PG 1407 + 265 is a factor of 25 more luminous than the median PG quasar from Schmidt & Green (1983) and only a magnitude less luminous that the multiple-image lens PG 1115 + 080. This interpretation would predict that the continuum is likely to fade on a timescale of decades (for a 1 $M_\odot$ lens; Dalcanton et al. 1994). However, the apparent strength of the Fe II emission, which would be unlensed, counts against this explanation. A quantitative measurement of the strength of Fe II (opt), not really possible with our current data because of the low signal-to-noise ratio near Hβ, would be important in evaluating the possibility of lensing. Deep CCD imaging could reveal the presence of any lensing galaxy at $z \sim 0.5$.

5. CONCLUSION

We have presented observations of an unusual quasar, PG 1407 + 265. The quasar has a normal nonvariable, radio-quiet continuum energy distribution, but the high-ionization emission lines are extremely weak and strongly blueshifted with respect to the low-ionization lines. We have discussed 10 possible explanations for the unusual spectrum, none of which is immediately convincing. Higher signal-to-noise ratio observations of the lines and detailed modeling will be required to resolve the mystery of PG 1407 + 265.

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Fig. 8.—Optical and ultraviolet rest frame energy distribution for PG 1407 + 265 compared with that of PG 1211 + 143 (data from Elvis et al. 1994). The plots cover the same range in logarithmic flux, so lines of identical equivalent width will appear the same. Line identifications are indicated.

REFERENCES

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Urry, C. M., & Reichert, G. 1988, NASA IUE Newsletter, 34, 95

Note added in proof.—M. Corbin (ApJ, 357, 346 [1990]) points out that PG 1407 + 265 lies on an extrapolation of the velocity shift–C IV equivalent width correlation discovered by him.