Quasars – powerhouses at the edge of time

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1999 was the 70th anniversary of Edwin Hubble's seminal publication[1] showing a cosmological redshift in galaxies. More recent discoveries of quasars have extended the universe's boundaries back in time nearer to the Big Bang. Some amateur spectrograms of quasars are presented showing a cosmological redshift.

Introduction

As late as the 1920s there was no positive proof that the innumerable *white nebulae* (galaxies) known to Herschel, Rosse and others were not part of our own Milky Way galaxy. In pioneering work Edwin Hubble used Cepheid variables discovered in nearby galaxies to determine an intergalactic distance scale, and in 1929 he announced that galaxies, beyond the Local Group, showed recessional redshifts as deduced from their spectra.

The Hubble Constant (H_0) characterises this relationship. The currently accepted value, refined by telescopes like the Hubble Space Telescope, is 65km ± 15km s^{-1} Mpc^{-1}. This is equivalent to 20km/s per million lightyears.

During the 1960s many radio sources were discovered and later linked to star-like objects (*quasi-stellar objects* i.e. QSO or quasars). Quasars proved to be highly redshifted active galactic nuclei that are intrinsically very luminous, although apparently faint in amateur terms due to their vast distances. Their discovery continues apace – in 1985 about 300 were listed[2] but today the tally has increased tenfold. Quasars provide an opportunity not only to probe deeper into space but to sample, through their spectra, the space in the line-of-sight towards them, sometimes aided by gravitational lensing of intervening galaxies.

The amateur rôle

What rôle can the amateur have in observing these enigmatic and remote objects? Although quasar 3C279 can peak about m_v 11.0 (an increase of nearly eight magnitudes during rare outbursts[3]), 3C273 at m_v 12.8 is commonly regarded as the brightest quasar. It is visible as a point of light in a 25cm or smaller aperture telescope, aided by suitable finder charts. Many dozens more are within range of the same telescope via film or CCD recording. Figure 1 shows a sample of quasar images captured, including two that are gravitationally lensed i.e. Q0957+561 split into two components, and APM 08279+5255 brightened twenty-fold to m_v 15.2 despite its extreme range as denoted by a high redshift. Table 1 lists the quasars observed.

But what of that spectrum of 3C273 that provides dramatic proof of the expansion of the universe since the Big Bang through a cosmological redshift? Was this within amateur range[4] from the unlikely location of a suburban garden with modest instrumentation?

Brightness *v* dispersion

In capturing a stellar redshift the amateur spectroscopist faces a dilemma. Stretching a singular point of starlight into a spectrum greatly dilutes the light (100-fold or 5 magnitudes fainter in the application to be described) and long exposures are needed to compensate. The brightest stars have relatively small radial velocities (blue- or redshifts – towards or away from the observer) and the necessary very high spectral dispersion results in very long exposures. As the velocities increase (in say nearby galaxies) the object brightness plummets and although lower dispersion is now acceptable the exposures are still exceptionally long.

Quasars essentially break the mould. They are disproportionally bright for their extreme range so that their

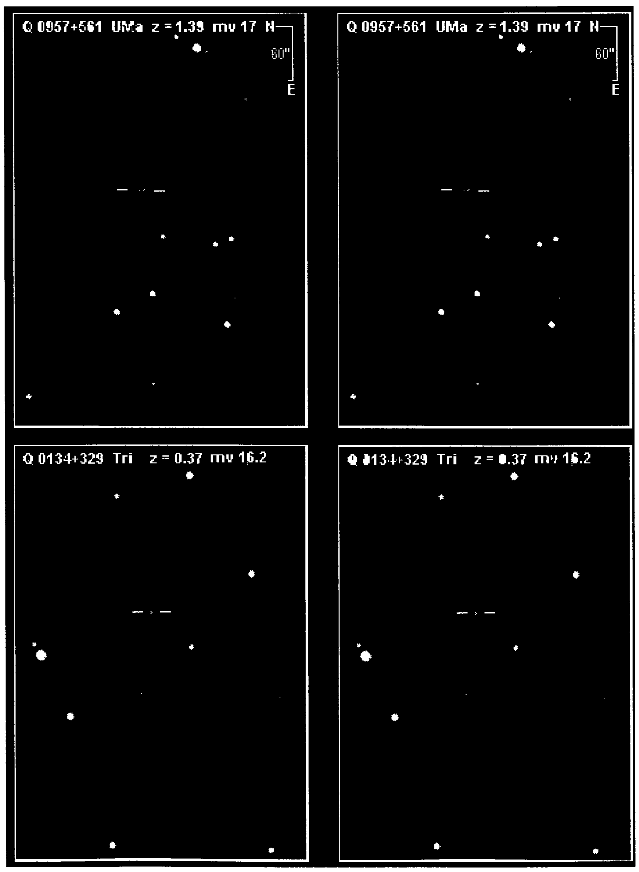

Figure 1. A selection of quasar images captured in 1998 December. 30cm Meade SCT + Starlight Xpress MX9 CCD camera; typical exposure 10m. *M. Gavin*

Table 1. List of quasars observed

QSO[1]	*RA* [J2000.0]	*Dec* [J2000.0]	*Const.*	m_v	*Redshift [z]* I	*Redshift [z]* II	*Exposure*
Q0014+813	00 17 09	+81 35.2	Cep	16.5	3.41		10m
Q0134+329 (3C48)	01 37 41	+33 09.6	Tri	16.20v	0.367		10m
Q0754+394	07 58 00	+39 20.5	Lyn	14.36	0.096	0.097	30m spec
APM08279+5255*	08 31 42	+52 45.3	Lyn	15.2	3.87	3.89	10m; 60m spec
Q0957+561*	10 01 21	+55 53.9	UMa	17.0	1.390		10m
Q1226+023 (3C273)	12 29 07	+02 03.1	Vir	12.86v	0.158	0.163	24m spec

* gravitationally lensed
I professional values
II estimated from the author's spectra

spectral lines are highly redshifted, and thus recordable with a very low dispersion spectroscope attached to a telescope of moderate aperture in modest exposures. Many quasars show emission lines and these are easier to record than dark absorption lines which are easily 'lost' against the object's bright background continuum, especially with low spectral resolution.

Targeting quasar spectra

The author made numerous attempts in the autumn of 1998 – rising before dawn – to secure a satisfactory spectrum of 3C273. Initially a home-made slitless prism spectroscope[5] was used, which previously had detected the broad Si II absorption band at 612nm in SN 1998bu.[6] The prism spectroscope was later substituted by a simple transmission grating[7] placed in the f/10 convergent beam of the telescope[8] some 20mm from the detector. Experiments had shown the latter arrangement was surprisingly efficient in forming an essentially linear spectrum 2mm long × 0.07mm high, with a dispersion of 180nm/mm or 4.12nm/pixel. The grating also forms a real point-like image of the object (zero order image) with a precise separation from its spectrum that aids alignment and measurement.

Early attempts were spoilt by watery skies and light pollution in the eastern sky. 1998 December 21 was a turning point. As the individual three and five minute exposures were downloaded the bright emission lines in 3C273's spectrum could be clearly seen on the PC monitor. The co-added exposures (24 minutes in total) reinforced the image and it was electronically stretched into a rectangular spectrogram.

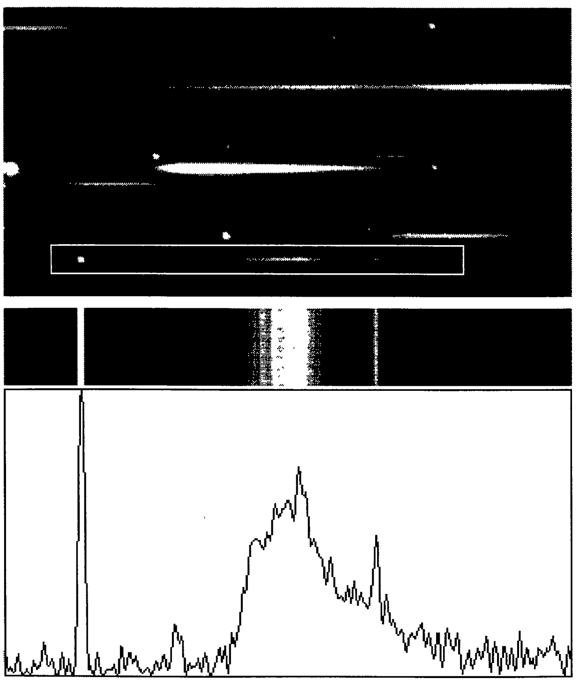

Figure 2. Starfield of quasar Q0754+394 in Lynx with quasar and its spectrum (boxed); spectrum electronically stretched (centre) and as intensity profile (bottom). 1999 Feb 9; 30cm Meade SCT + grating spectroscope + MX9 CCD; 30m integrated exposure. *M. Gavin*

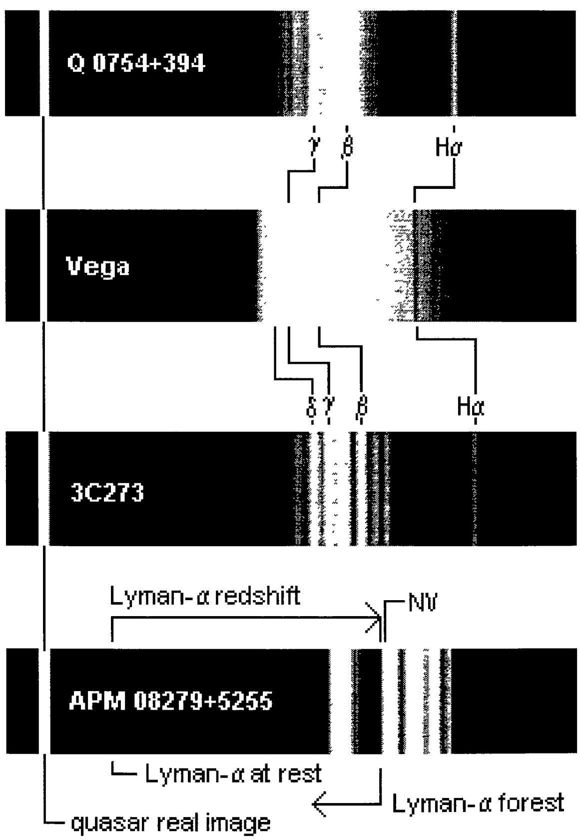

Figure 3. Spectrograms of three quasars recording a redshift and aligned against their 'real' images (zero order spectra) to the left. Vega is used as a fixed comparison spectrum. *M. Gavin*

More spectra

A further spectrogram of quasar 3C273 taken on 1999 January 14 confirmed the initial results and provided the catalyst to target two more quasars on 1999 Feb 9/10, i.e. Q 0754+394 (Figure 2) and APM 08279+5255,[9] both in Lynx. Figure 3 shows all three spectrograms. APM 08279+5255 is highly redshifted (z=3.87) – to the point that the visible spectrum is 'lost' into infrared whilst the normally invisible UV spectrum is transferred into the visible region. At m_v 15.2 the quasar's spectrum proved an exceptional challenge near the limit of detection in an hour's exposure.

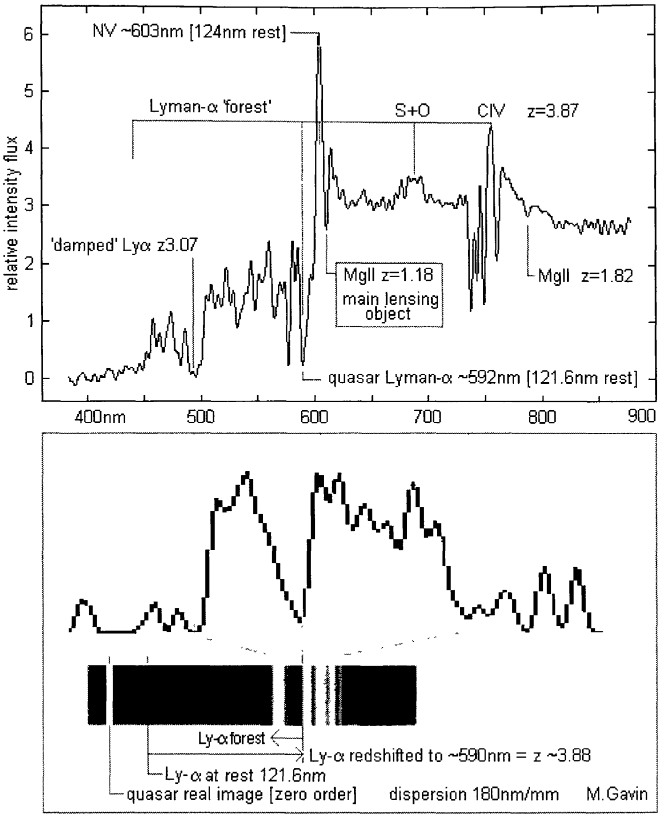

Figure 4. The author's low resolution spectrum profile of APM 08279+5255 (lower box) compared with a professional spectrum[13] sampled to 5nm (upper box).

Analysing results

No attempt was made to calibrate the spectra for instrumental and other effects. The object of the exercise was to detect lines in the quasar's spectrum and measure their shift redwards. The minimum detectable radial velocity (set by the spectrum scale of 4.12nm/pixel) was ~800km/s. This was vastly in excess of Vega's modest velocity of –14km/s, so that the star's spectrum could form a fixed (at rest) comparison to the quasar's redshifted spectrum. Likewise the various other local motions that can affect results i.e. the Earth's orbital motion about the Sun, the Sun's about the galaxy and the galaxy about the Local Group are all negligible in this context.

The formula for calculating z is straightforward i.e. [1]

$$z = (\text{new wavelength} - \text{wavelength at rest}) / \text{wavelength at rest}$$

It is unnecessary to know the actual at rest and redshifted wavelengths to derive the z value – a simple pixel count from the object's real image (zero order spectrum centroid) to the spectral line establishes this relationship, as in Table 2. In the case of APM 08279+5255, Vega's spectrum is of no value (except to set a dispersion scale) and the rest positions of Lyman-α and NV in UV were estimated. All derived z values are within ~3% of published z values which is an acceptable result for the very low spectral dispersion used.

Table 2. Measured z values of observed quasars (dispersion 4.12nm/pixel)

Spectral line	*Pixel count** *Vega (at rest)*	*Quasar (redshifted)*	*z value Derived*	*Avge.*	*Estim. velocity ****
3C273					
Hα	159.5	185	0.160		
Hβ	118	136.5	0.157		
Hγ	105	122	0.162		
Hδ	99	116	0.172		
				0.163	0.15c
Q 0754+394					
Hα	159.5	175	0.097		
Hβ	118	129.5	0.098		
Hγ	105	115	0.095		
Hδ	99	–	–		
				0.097	0.09c
APM 08279+5255					
Lyα (121.6nm)	29.5**	144	3.88		
NV (124.0nm)	30**	147	3.90		
				3.89	0.92c

* pixel count from centroid of real image (zero order spectrum)
** estimated from rest wavelength
*** corrected for relativistic effect of high redshift

Notes on the spectra

It was fascinating to find the redshifted quasar spectrum did not simply slide sideways en bloc but expanded with increasing wavelength – the Hα line appears displaced more than Hβ and so on (Figure 3). In reality the wavelength shift is proportional to the rest wavelength [equation 1, i.e $z = (\lambda - \lambda_0) / \lambda_0$] so as we move to the blue the shift gets less.

The *A* line at 759.4nm in red (oxygen in the Earth's atmosphere) is one of the strongest lines recorded in ground-based spectra especially at sea-level, and appears superimposed on all stellar spectra. The Hα emission line in 3C273 is coincident with, and appears partially masked by, the *A* line. In Q 0754+394 the Hα emission line is clear of the *A* line and records much more strongly.

APM 08279+5255 was targeted for its high redshift without prior knowledge of its spectrum. When captured it was quite unlike any previously recorded. The spectrum appeared broken into two segments by a broad absorption band and an anticipated strong Lyman-α emission line (121.6nm at rest) was absent.

An explanation was forthcoming from a contributing author[10] to the original published paper.[11] APM 08279+5255

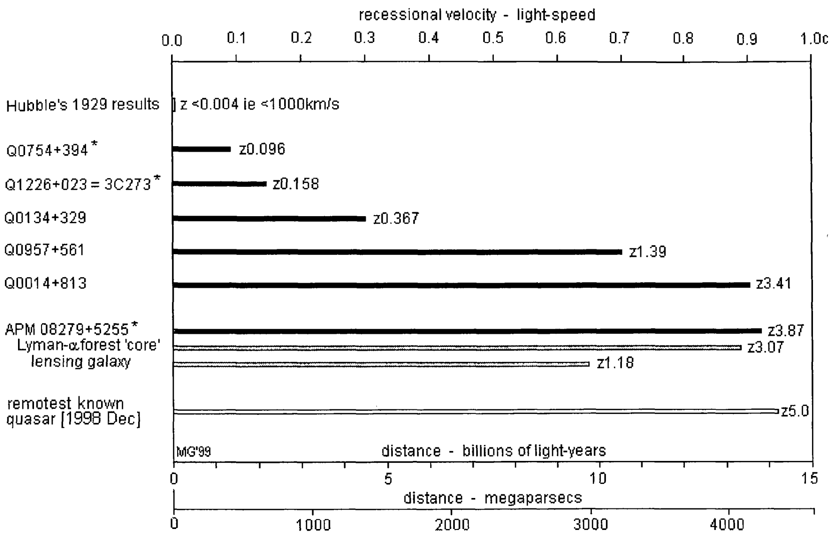

Figure 5. Plot of observed quasars (black bars) against recessional velocities/distance. Spectra obtained from Worcester Park marked *. *M. Gavin*

is defined as a Broad Absorption Line quasar whereby self-absorption of assorted lines such as Lyman-α occurs. The intervening Lyman-α forest removes much of the flux blueward of Lyman-α (as with all high redshift quasars) making Lyman-β and O VI (ionised oxygen) much harder to record. The damped Lyman-α candidate is basically cold gas, thought to be disc-like 'proto' galaxies along the line of sight. The Mg II absorber, annotation at z=1.18, is attributed to the main lensing object. Figure 4 compares the professional spectrogram with that of the author.

Trimming velocities

A small z value may be taken as the object's true velocity proportional to light-speed and this can be verified in the laboratory. However if the lines in an object's spectrum are shifted to double their rest wavelength (z=1) the object would apparently be receding at the velocity of light (c) and thus unobservable, for no photons could reach the telescope! A more complex formula is needed to take relativistic effects[12] into account to keep the object's velocity (v) below light-speed:

$$v/c = (z + 1)^2 - 1 \;/\; (z + 1)^2 + 1 \qquad [2]$$

At z=1 recessional velocities are about 60% of light-speed and at z=3 about 90%. Further discoveries (currently z=5) only make small inroads towards the unachievable 100% or light-speed itself.

Even quasars 3C273 and Q 0754+394 with a modest z<0.2 must take relativistic effects into account and their recessional velocities (Table 1 and Figure 5) are trimmed back slightly from their z value. High redshift quasar APM 08279+5255 (z=3.87) is apparently receding at a remarkable 0.92c rather than an implausible 3.87c. This quasar also samples, through its spectrum, the Lyman-α forest of absorbing gas clouds in the line of sight immediately before the quasar itself (thus less redshifted) and (in the professional spectrogram) the lensing object at z=1.18. Effectively we view this quasar and its environs early in the history of the Universe.

Summary

As singular points of light quasars do little to inspire the eye but hopefully the mind's eye will be fulfilled when the colossal distances, velocities and energy of these objects are contemplated. The World Wide Web is a fruitful source of further information and the author maintains a webpage on the practical observation and capture of quasar spectra at

http://www.astroman.fsnet.co.uk/quasars.htm

Acknowledgments

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