Very high redshift quasars with VISTA

Contributors : R.G. McMahon(IoA), S.J. Warren (ICSTM), P.C. Hewett (IoA), M.J. Irwin(IoA), R.G. Sharp(IoA)
Date : 2000 Jan 27th

SUMMARY

We propose to carry out a series of nested multi-colour surveys over 1000 to 10000 deg^2 to search for quasars with $5.5 < z < 7$. The primary goals are:

- to establish the space density and form of the quasar luminosity function at the earliest epoch possible.
- to identify the most luminous quasars in the high redshift Universe in order to facilitate detailed absorption-line studies of the metallicity, ionization state, dynamics and clustering properties of the baryonic content of the Universe.

At this stage there are significant sources of uncertainty in designing the survey. The situation will improve to some extent before observations begin, but a flexible survey campaign is desirable, allowing modification on the basis of the results as the survey progresses.

Except where explicitly mentioned all quoted magnitudes are on a Vega based normalisation.

---

1 Science Case

The most distant quasar currently known is at redshift $z \sim 5$ and was discovered by the Sloan team. Quasars at larger redshifts still will provide vital clues to the processes involved in the formation of the first bound objects. We propose to use the power of VISTA to survey for the first quasars, opening up the redshift range $5.5 < z < 7$. The principal scientific goals are the following

- to determine the epoch of reionization of the Universe via the Gunn-Peterson test.

- to establish the contribution of AGN to the integrated extragalactic background light(EBL) and in particular the meta-galactic UV background at z>5, and hence determine the major source of ionization of the high redshift Universe.
- to measure the chemical, ionization and dynamical state of the intergalactic medium, where most of the baryonic content of the Universe will reside, at the earliest epoch possible and to compare this with numerical simulations.
- to establish unambiguously the total UV luminosity density in the high redshift Universe due to quasars via the explicit detection of the characteristic break or knee in the quasar luminosity function out at z>6
- to identify a sample of z>5 quasars suitable for the detection of damped Lyman-α absorbers to measure the cosmic density of neutral gas in the high redshift Universe.

While there is little doubt that the quasar population reaches a peak in the redshift range 1.5 to 3.0 and that the total space density of optically selected quasars at higher redshifts is declining (Warren, Hewett& Osmer 1994; Schmidt, Schneider and Gunn 1995) the high redshift (z>4) luminosity function is basically unknown, as illustrated in Figure 1. The lack of knowledge is particularly acute at fainter magnitudes and at z>5. Over the next few years we can expect considerable progress and for $4 < z < 5$ the quasar luminosity function will become quite well established as the result of work based on the SDSS, INT WFS(McMahon, Sharp etal), CFHT 12K(Crampton, Hook, McMahon, Schade) and a number of other deeper multi-colour surveys that are currently in progress.

In other respects the return from current surveys will be limited. For example many of the luminous $z > 4$ in the Sloan survey area have already been discovered using Schmidt plates. Similarly it is unlikely that SDSS will find many (if any) quasars above z>5.5 since SDSS is a shallow survey t=55secs at a mediocre site(1-1.5" seeing) and the reddest band is the Gunn z band. To make a significant step forward requires IR observations. For VISTA we assume the minimum redshift of interest in the context of high redshift quasars is $z = 5.5$. The combination of depth, and extension to the near-infrared, will allow VISTA to survey for quasars over the redshift range $5.5 < z < 7$.

2 Technical Case

Wavebands required

To make a significant step forward we assume the minimum redshift of interest for VISTA is $z = 5.5$. The multicolour technique works best at high redshift using up to four bands: i) a blue band lying immediately blueward of the Lyman limit(λ_{rest}=912Å), ii) two bands that straddle blueward and redward of the Lyα line(λ_{rest}=1216Å), iii) a red band at as long a wavelength as possible, but still blueward of the peak of the black-body curve for the red stars against which the quasars are being discriminated. J is preferred because of faster survey speed.

The above considerations indicate the use of the combinations r, i, J for $5.5 < z < 6.0$, and i, z, J for $6.0 < z < 7.0$. In reality one would use multi-dimensional analysis using all 4 bands simultaneously.

Simulation of a two-colour diagrams indicating quasar selection for these redshift ranges are shown in Figure 3. These simulations require an extrapolation beyond z$\sim$4.5 of our knowledge of the properties of intervening absorbers. As more quasars of $z \sim 5$ our discovered this uncertainty will be reduced.

On this basis for a survey magnitude limit (S/N=10) in J, the required survey depths in the other bands are as follows: $r = J + 4.0$, $i = J + 3.0$, $z = J + 1.0$.

Note that the simulations in Figure 3, take no account of contamination of the colour-colour space by misclassified red galaxies. In particular we need to include the evolved elliptical galaxies and EROs(Extremely Red Objects). It is important also to realise the success of high redshift quasar surveys depends not just on the number of candidate quasars but on the ratio of candidates to true quasars. This ratio is currently unknown since neither the numerator or denominator is known.

Expected surface densities and magnitude limits at z>6

To satisfy some of the science goals of this program we do not necessarily need large numbers of objects in the first stage. At the highest redshifts even one object would be enough. However to guarantee success one should aim to detect 10 objects in the case of the optimistic scenario and then proceed to larger area or fainter flux limits in the next phase.

Also, the current uncertainty in the evolution of the quasar luminosity makes it pointless to try to design a survey that will answer everything. We therefore propose a series of surveys that are incremental with branch points. To maximise the final return it will be important to execute the first stage as early as possible.

To determine a statistically significant(3σ) space density one requires $\sim$10 objects ie $N/\sqrt{N} \sim 3$. This logically leads one towards surface densities of 10^{-2} deg^2 if you expect to get significant estimate in 1000deg^2. Also one has the potential of still doing a survey which is 10-15 times higher ie all the high latitude sky visible to VISTA, should one want to expand the survey significantly at a later date.

Figure 3 shows the predicted number of high redshift(5<z<7) quasars per square degree for two parameterizations of the quasar luminosity function. Since for work at z>6 we shall need at least one IR band we quote our surface densities in the J band.

From Figure 3a based on WHO we see that one needs to reach J=22.5 to reach a surface density of 1 quasar at z>6 in 100deg^2. From Figure 3b based on SSG, we see that one need to just get to J=19 to reach a favourable surface density. A reasonable best bet first phase would be to survey 1000deg^2 to J=20.5 as soon as possible and then design a second phase on the basis of this. The second phase could be either deeper over the same area of to the same depth or shallower over a larger area.

3 Summary of Requirements, and key tradeoffs

- **Area:**
  - 1000deg^2 for survey A (should be done in 2DF + XMM XID survey regions)
  - 1000deg^2 for survey B (should be done in 2DF + XMM XID survey regions)
  - 5–10,000deg^2 for survey C (ie almost all $|b|$ sky visble for N and S hemispheres)
- **Wavebands:**
  - **optical bands** r, i and z [g would be useful for 4<z<5.5]
  - **IR bands** J
- **Any specialised filters required:** None
- **Depth in each band:**
  - J=20.5(10sigma) for survey A; r=24.5; i=23.5; z=21.5(10sigma)
  - J=21.5 for survey B; 1 mag fainter than A
  - J=20.5 for survey C; as A

  A total S/N of 20 is required to facilitate star galaxy separation especially since at these magnitudes galaxies outnumber z>5.5 quasars by $>10^4$.
- **Spatial resolution:** FWHM<1" is essential for efficient star galaxy.
- **Astrometric accuracy:** 0.5"
- **Time sampling pattern:** None but IR and optical data should be quasi simultaneous to avoid galactic variables or SN contaminating the quasar sample. Long term variability could maybe be used to screen candidates. Lets say we take two I band images 5 years apart.
- **Spatial sampling pattern:** None
- **Photometric accuracy:** S/N of 10 in redder 2-3 bands. If survey is contiguous MAYBE non-photometric conditions could be used.
- **Reliability and completeness required:** Upper limits for magnitudes will be required when objects are detected in a redder bands but not detected in the bluer bands; 99.9% reliability is required otherwise we will be swamped by spurious quasar candidates, since at the flux limits we need to attain, stars and galaxies outnumber quasars 10^{4-5} to 1.
- **Timescale on which the programme would be of interest:**
  - survey A needed ASAP so that choice between B and C can be taken as early as possible.
- **Estimated time to completion.**
  - 1 year for survey A (20nights per band)

  - 5 years for survey B (100nights per band)
  - 5 years for survey C (100nights per band)

- **Other issues:** J needs only 100secs per pointings which may require a special observing strategy to minimise the overheads and dither strategy. Note that even with 6pt dithering and 1.3 sec per read out, 2MASS claim 85% observing efficiency.

Table 1: Nominal photometric S/N=5 survey limits in AB and Vega magnitudes; as an independent check on VISTA predictions we includ comparisons with SDSS throughput

		SDSS 2.5m + 55s		WFS[1] 2.5m + 600s		WFS[2] 2.5m + 600s		VISTA[3] 4.2m + 900s		Proposal VISTA[4] 4.2m + 900s	
Waveband	AB mag[5] of Vega	AB	Vega	AB	Vega	AB	Vega	AB	Vega	AB	Vega
u'	+0.98	22.1	21.1	23.4	22.4	24.6[6]	23.6[6]	24.4	23.4	26.3	25.6(U)
g'	−0.09	23.3	23.4	24.6	24.7	25.0[6]	25.1[6]	25.6	25.7	26.5	26.5(V)
r'	+0.17	23.0	22.8	24.3	24.1	24.3	24.1	25.3	25.1	25.5	25.3(R)
i'	+0.40	22.4	22.0	23.7	23.3	23.7	23.3	24.7	24.3	25.1[8]	24.7(I)[8]
z'	+0.57	20.8	20.2	22.1	21.5	22.2	21.6	23.1	22.5	24.8[8]	24.2(z)[8]
J	+0.90									24.3	23.4
H	+1.37									23.3	21.9
K	+1.88									22.8	20.9

Notes:
(1) INT WFS limiting magnitudes are scaled from the SDSS nominal limits which assume seeing of 1"[see www.sdss.org].
(2) Actual WFS survey limits in 1" seeing (3) VISTA limits scaled from SDSS (4) From VISTA proposal and values circulated in KP pro forma.
(5) Vega normalisation for Sloan AB system from Fukugita et al(1996), AJ, 111, 1748
(6) WFS U and g' are better than SDSS due to more modern blue sensitive CCDs. Note also that the INT U throughput is down by 30% due to corrector recoating delays; ie should be 0.15mag better
(7) For S/N=5 add 0.75 magnitudes. SDSS to INT=+1.30mags; INT to VISTA=+0.80 magnitudes; 600secs to 900secs add 0.22magnitudes
(8) proposal assumed Z would use IR detector; if VISTA uses deep depletion devices i and z should be a factor of 2 better than SDSS/INT chips (9) JHK zeropints from Bessel & Brett(1988), AJ, 100, 1134. (11) All results are for stars with gaussian profiles. For resolved galaxies limits are around 0.5mag worse.

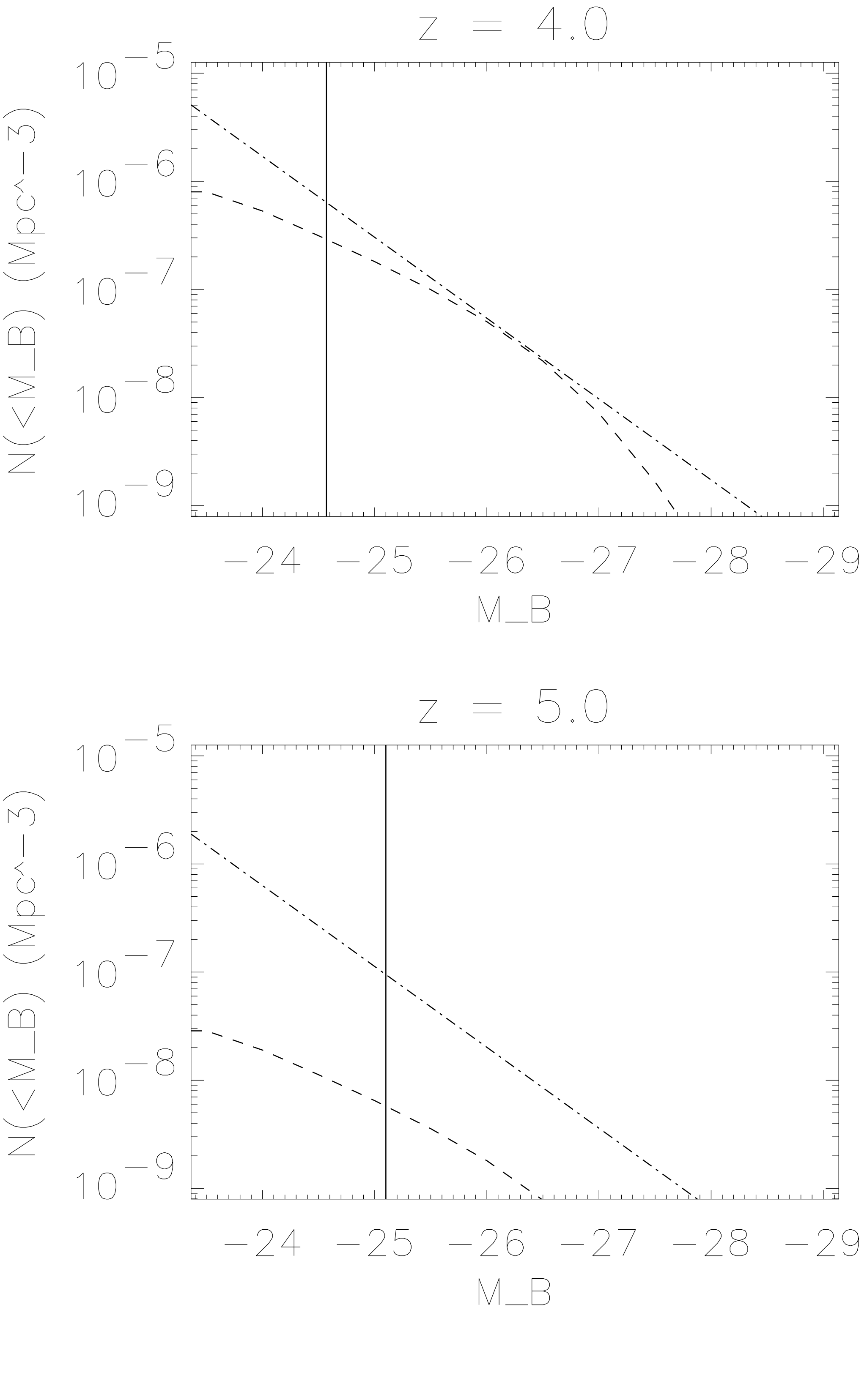


Figure 1: For illustration we shown two recent parameterisations of the quasar luminosity function (dashed - Warren, Hewett & Osmer 1994 , dot-dash - Schmidt et al. 1995) are shown computed at redshifts 4 and 5. Whilst there is good agreement at z=4 at $M_B \sim -26$, which is close to the regime encompassed by the input observations, by a redshift of 5 the extrapolated luminosity functions are quite different. The vertical line indicates the absolute magnitude of a quasar at a effective survey limit of z'=21.0(Vega normalisation) which is the regime that is being probed by current surveys

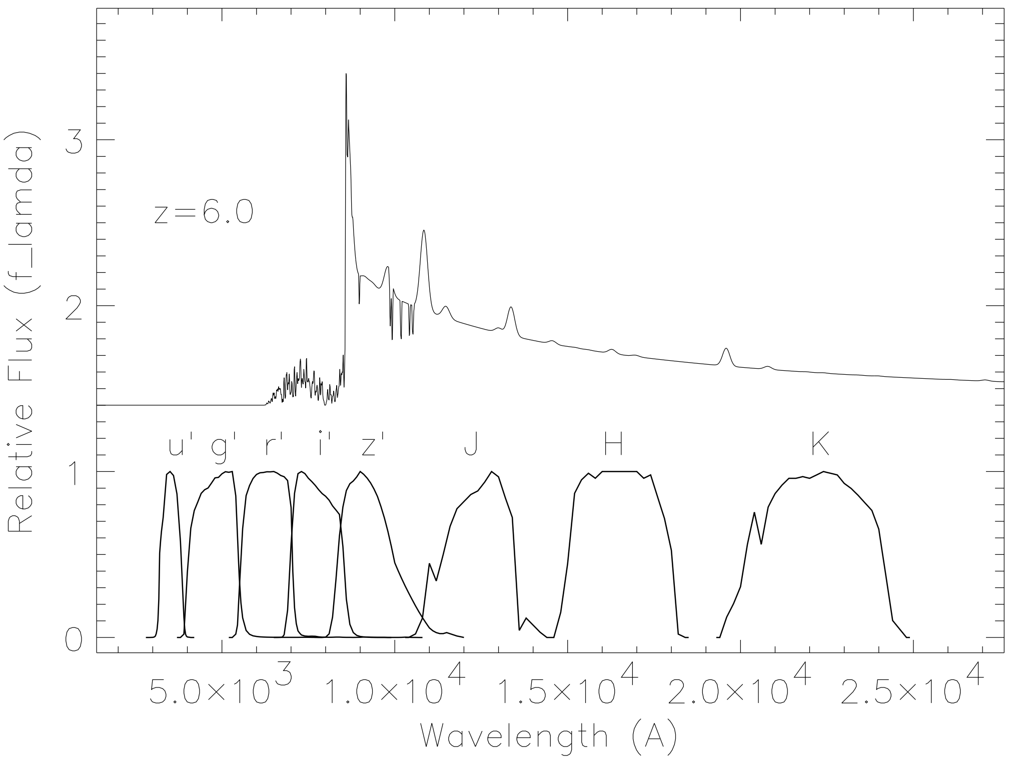


Figure 2: Synthetic quasar spectrum based on a power law with spectral index ($S_\nu \propto \nu^{-0.7}$) with an emission line spectrum based on the Francis et al.(1991) composite spectrum. Absorption due to the intervening Lyman-α forest and metal line systems has been monte-carlo simulated on the basis of an absorption line population described by the parameters derived by Williger et al.(1994) for the forest and by Storrie-Lombardi et al.(1994) for the optically thick lyman-limit absorption systems

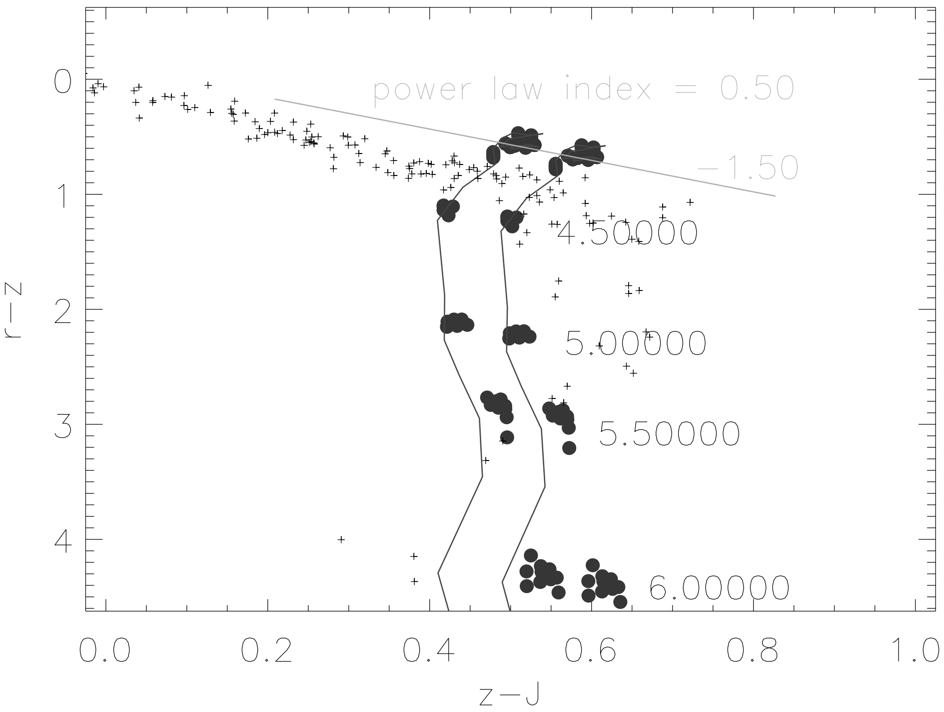
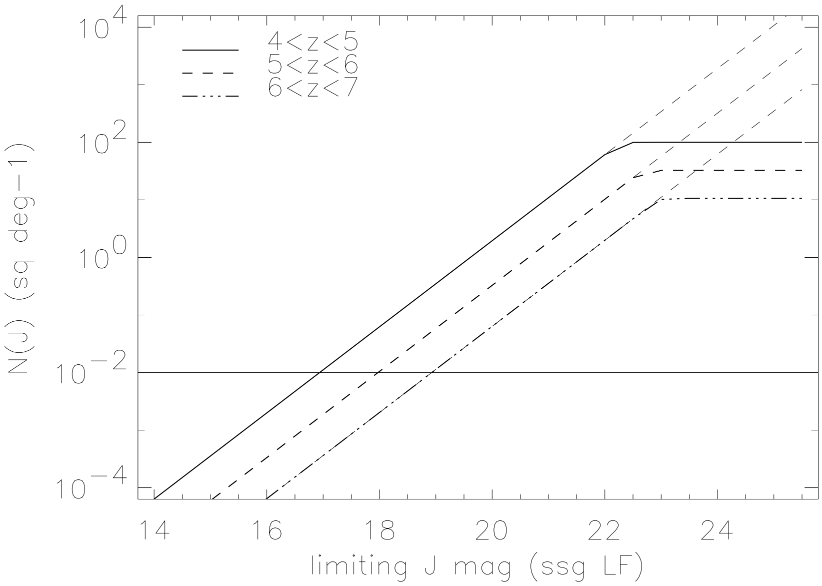


Figure 3: Theoretical r-z, z-J colour-colour diagrams. The crosses are colours for stars calculated using the Gunn & Stryker(1991) stellar atlas with the Persson extension into the IR(from SYNPHOT in STSDAS). The filled circles are quasar colours that have been simulated using the monte-carlo approach described above for two different continuum spectral indices -0.50 and -0.75. The solid wobbly line is quasar colours calculated using the analytic IGM model proposed by Madau 1995. The differences between the two approaches are beyond the scope of this study. The solid line near the top shows the effect of underlying spectral index on colours. Yes, we could also add a reddening vector.



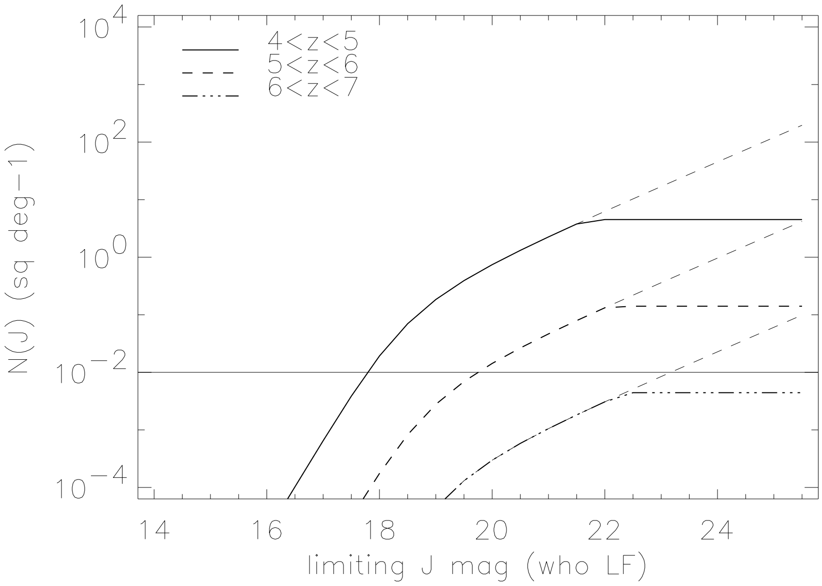


Figure 4: The predicted number of quasars per square degree as a function of apparent J magnitude is shown for the two luminosity functions in figure 1. The horizontal line indicates a fiducial surface density of 1 quasar per 100 deg^2. To convert to a K band limit assume J−K=1.0; ie J=20 is equivalent to K=19.