Multifrequency observations of the red QSO 1413+135

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The extremely red QSO 1413+135 shows characteristics typical of BL Lac objects—no emission lines, is embedded in a luminous galaxy, is subject to rapid radio and IR variability, has an inverted radio spectrum and shows substantial IR polarization. The rapid steepening of the nonthermal spectrum at $\lambda < 5$ μm is interpreted as synchrotron emission from an electron distribution that ends sharply at some maximum energy. The X-ray emission is probably inverse Compton radiation. We calculate that the optically thin emitting region is compact, has a large magnetic field and exhibits bulk relativistic motion towards the observer. The most energetic electrons in the emitting region have a Lorentz factor of 10^2–10^3.

ATTEMPTS to determine the physical conditions of the continuum emitting regions of QSOs have failed to obtain well defined values for the model parameters because the data can be interpreted equally well by a wide variety of models. Because of its unusual spectrum, the red QSO 1413+135 proves an exception in this respect. We report here simultaneous observations of the continuous spectrum of 1413+135 from which we make the first estimate of the maximum energy of the electrons in a synchrotron source. We can also determine other parameters such as source size and magnetic field with improved accuracy.

Red QSOs[1-3] share several properties with BL Lac objects and optically violent variable QSOs (OVVs): they are strong flat-spectrum radio emitters, variable on a time scale of weeks or less, and frequently lack emission lines. The distinguishing characteristic of red QSOs is the extremely steep decline in their continuous spectrum between IR and optical wavelengths. In terms of the energy flux distribution $F_\nu \propto \nu^{-\alpha}$, the characteristic spectral index $\alpha \simeq 3$. Consequently they are readily detected in the IR, but very difficult to observe optically[2]. The characteristic steep spectra of red QSOs is believed to be an intrinsic property of these objects, and not the result of selective extinction[2,4].

The red QSO 1413+135 is particularly suited to detailed study because it is one of the brightest members of its class at radio and IR wavelengths. By determining the redshift and monitoring the IR and radio flux, we have obtained essential information on the size of the emitting region. We have also obtained nearly simultaneous observations of the continuous spectrum in the radio, IR and X-ray bands. The IR observations provide a good determination of a cutoff in the spectrum. The composite spectrum permits determination of the parameters of a simple theoretical model, that is size, magnetic field and bulk velocity and the maximum energy of the synchrotron electrons. The key element in the analysis is that the unusual shape of the steeply falling IR spectrum of 1413+135 places strong constraints on theoretical models of the source of its continuous emission.

Observations

Near IR observations of 1413+135 were obtained with the 1.54-m and 2.25-m telescopes of the University of Arizona with the same IR photometers used previously. Apertures of 8.5 arc s and 7.8 arc s, with spatial chopping of 10 arc s, were used respectively with the two telescopes (calibration procedures are described elsewhere (ref. 5 and G.H.R. unpublished data)). The most extensive measurements, obtained at K (2.2 μm), provide additional information on the variability of the source (Table 1).

During January 1980 we obtained IR photometry of 1413+135 out to 10.6 μm, which are normalized to the flux level measured at 2.2 μm on 24 January 1980 (Table 2). Measurements at 2.2 μm were obtained within 1 h of the measurements at the other wavelength to facilitate this normalization. The major conclusion from this photometry (Fig. 1)—that the spectrum becomes less steep beyond 5 μm—has been discussed elsewhere[6] and confirmed by subsequent measurements[7].

We also measured the polarization of the source at 2.2 μm on 26 January 1980 and found it to be 16±3%, at a position angle of 175°±5° (the instrumentation is discussed in ref. 8).

Our new observations support the suggestion that the exceedingly steep spectral slope of 1413+135 is not a result of reddening of an otherwise normal quasar spectrum[2,4,7]. Given the redshift of 1413+135, the extinction of absorbing material must be large ($A_v \simeq 6$) if the IR spectrum was originally a simple power law of slope ~1.5. This extinction would imply a high degree of multiple scattering at 2.2 μm, which could depolarize the source, in disagreement with observations. Furthermore, when the observed spectrum is corrected for such large absorption, it would have an optical–IR to radio luminosity ratio

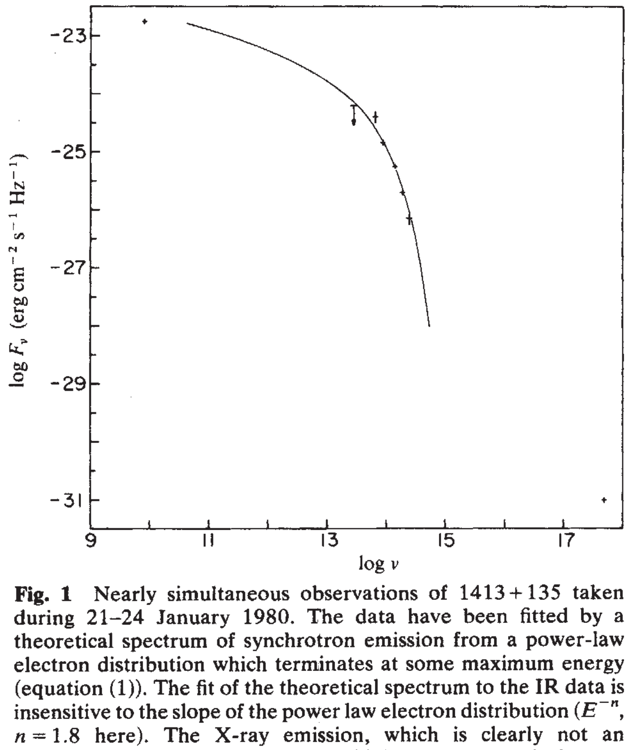

Fig. 1 Nearly simultaneous observations of 1413+135 taken during 21–24 January 1980. The data have been fitted by a theoretical spectrum of synchrotron emission from a power-law electron distribution which terminates at some maximum energy (equation (1)). The fit of the theoretical spectrum to the IR data is insensitive to the slope of the power law electron distribution (E^{-n}, $n = 1.8$ here). The X-ray emission, which is clearly not an extrapolation of the IR continuum to higher energy, may be inverse Compton radiation.

0028-0836/81/440714—04$01.00

Table 1 Variability of 1413+135 at 2.2 μm

Date	Flux (mJy)	Ref.
10 February 1979	3.32±0.10	2
7 March 1979	1.72±0.12	2
8 March 1979	1.98±0.18	2
24 January 1980	5.5 ±0.3	This work
25 January 1980	4.6 ±0.2	This work
26 January 1980	3.7 ±0.2	This work
10 February 1980	2.55±0.2	7
27 February 1980	4.2 ±0.2	This work
26 April 1980	2.35±0.2	This work
21 May 1980	2.0 ±0.2	This work
22 May 1980	1.8 ±0.15	This work
23 May 1980	2.6 ±0.2	This work
21 July 1980	1.71±0.09	7
25 July 1980	2.15±0.20	7
4 August 1980	1.98±0.10	7
5 August 1980	1.76±0.14	7

substantially larger than what is observed in all other flat spectrum radio sources[9].

We have located 1413+135 accurately on the Palomar Sky Survey plates and confirm the original PKS position and finding chart[10]; the finding chart given by Condon *et al.*[11] is incorrect. The positions of the source measured in the radio, IR, optical and X-ray bands are identical, to within measurement error. The optical image is red and clearly extended, and we suggest that it is a distant underlying galaxy. An optical spectrum of this galaxy, obtained at the Multiple Mirror Telescope, shows the H and K break at 5,000 Å, corresponding to a redshift of $z = 0.26 \pm 0.01$ (Fig. 2). At this redshift, the next accessible strong absorption features expected in the spectrum of a giant elliptical galaxy are Hδ and CH; these features are present in the data, at modest signal-to-noise ratio. There are no emission lines, and the nonthermal continuum is overwhelmed by the galaxy at ~0.5 μm.

X-ray observations of 1413+135 were made with the Image Proportional Counter on the Einstein Observatory as part of Guest Observer Programs 246 and 547. The first observation, which was made on 21 January 1980 (UT) with an integration time of 6,111 s, revealed a weak source coincident with the established position of 1413+135. The net counts in the 0.19–3.63 keV region (ch. 3–13) were 48.3±13.9 (3.5σ). During 24 January 1981, a second observation was made with an exposure time of 11,954 s. The net counts in the 0.19–3.63 keV region were 148±18.6 (8σ). It is not possible to determine whether the difference in the counting rates between these two observations is significant (0.0079±0.0023 c.p.s. (counts per s) for 1/80 and 0.0124±0.0016 c.p.s. for 1/81, a 1.6σ difference).

To convert the counting rate to fluxes, we used a column density for neutral hydrogen of 1.4×10^{20} cm^{-2} (estimated from ref. 12) and a range of (unknown) X-ray spectral indices of 0.75, 1.5 and 3.0. Average values for the integrated fluxes (0.19–3.63 keV) and monochromatic fluxes (2 keV) are 1.59×10^{-13} erg cm^{-2} s^{-1} (1/80), 2.50×10^{-13} erg cm^{-2} s^{-1} (1/81) and 1.47×10^{-5} keV cm^{-2} s^{-1} keV^{-1} (1/80), 2.31×10^{-5} keV cm^{-2} s^{-1} keV^{-1} (20% systematic uncertainty in the conversion to fluxes).

The peculiar IR–optical spectrum makes it difficult to compare the X-ray brightness of this object with that of other QSOs. While the ratio of X-ray to optical flux ($\alpha_{ox} = 1.3$) is typical of BL Lacs or QSOs (refs 13, 14 and W.H.-M. Ku, personal communication), the X-ray to IR flux ratio ($\alpha_{ix} = 1.6$) is larger than the mean of radio bright QSOs[13].

The flux density and linear polarization of 1413+135 were observed at 4.8, 8.0 and 14.5 GHz using the University of Michigan 26-m paraboloid (instrumentation and reduction described elsewhere[15,16]). These flux density measurements were corrected for source polarization and are on a flux density scale in which 3C274 has assumed fluxes of 70.0, 48.6 and 29.9 Jy at 4.8, 8.0 and 14.5 GHz respectively.

Figure 2 clearly illustrates that the radio spectrum was inverted during the entire observing period. Between June and August 1980, the source increased its flux at 14.5 GHz by 100%, giving us a time scale for flux variation ($F\mathrm{d}t/\mathrm{d}F$) of about 3 months. As the source became brighter, the spectrum became more steeply inverted; α ($F_\nu \propto \nu^{-\alpha}$) decreased from −0.2 to −0.9. A second outburst, which occurred from January to April 1981, has properties similar to those of the first outburst: the flux changes occur simultaneously at all three frequencies but the intensity of the outburst is greatest at the highest frequency (14.5 GHz).

Both the lack of any detectable time delay between the peak at 14.5 and 8.0 GHz and the relative amplitude of the outburst at these frequencies are inconsistent with the simple expanding source model[17]. The ratio of the amplitude of the outburst at 14.5 GHz compared with that at 8.0 GHz is considerably greater than most outbursts in other sources. The spectral slope ($\alpha = -\mathrm{d}\log F/\mathrm{d}\log \nu$) of the flux increase (first outburst) is $\alpha = -2.5 \pm 0.3$; the second outburst has a similar value of α. Because a homogeneous optically thick synchrotron source has a spectral index of −2.5, these outbursts may be caused by newly injected or newly shocked plasma that is optically thin at IR frequencies and becomes optically thick somewhere in the far IR to millimetre region. If the cooling time of synchrotron-emitting electrons equals the decay time of the outburst, $B \gtrsim 1$ G, which is consistent with the analysis of the simultaneous spectrum.

In contrast to the large IR polarization, we have not detected any linear polarization in the source at radio wavelengths. Averages of the 1980 data yielded degrees of polarization of 0.5±0.3, 0.4±0.5 and 1.4±0.7% at 4.8, 8.0 and 14.5 GHz respectively.

Discussion and interpretation

The above observations strengthen the association of 1413+135 with the BL Lac objects. In addition to the absence of emission lines (this work and ref. 7), the IR flux variations (Table 1) place 1413+135 among the most variable extragalactic sources known. On two occasions (late January 1980 and late May 1980), changes >20% were observed on time scales of 1 day and, on three occasions, the intensity changed by a factor of two in a month or less (Table 1). Among well studied sources, none show a significantly higher level of IR activity, and only a few (for example, BL Lac, OI 090.4) display comparable variability (see ref. 18 and refs therein). Similarly, 1413+135 is one of the most rapidly variable radio sources, exhibiting a 100% flux increase at 14.5 GHz in a little less than 3 months. The high level of IR polarization also supports the suggestion[2] that the source is a BL Lac object. Only one-third of the BL Lac objects listed by Angel and Stockman[18] have larger polarizations than that of 1413+135. Its low degree of radio polarization is not

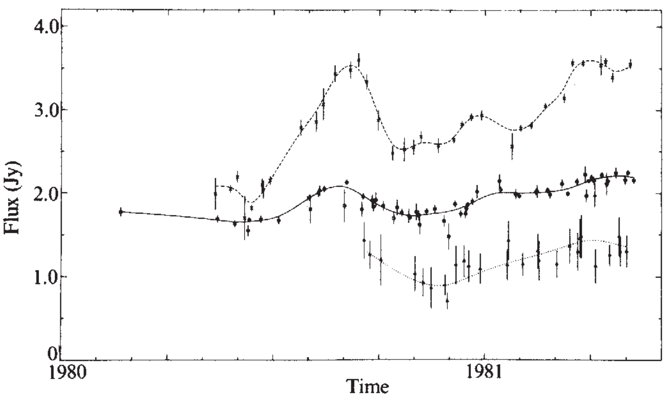

Fig. 2 The radio observations of 1413+135 show that this source is extremely active at 14.5 GHz (×) and less active at 8 GHz (○) and 4.8 GHz (△). The radio spectrum, which is always inverted, becomes most steeply inverted during outbursts ($\alpha = 0.9$). The rate of flux increase during the June–August 1980 and February–April 1981 outburst are nearly identical.

Table 2 IR spectrum of 1413+135 on 24 January 1980

Wavelength (μm)	Flux* (mJy)
1.25	0.76±0.11
1.6	1.92±0.17
2.2	5.48
3.5	14.5±1.2
4.6	39±10
10.6	≤63 (2σ)

* Flux values have been corrected for filter bandpass effects to the equivalent monochromatic flux at the indicated wavelength.

unusual for BL Lac-type objects, although several BL Lac objects display high radio polarization. Another similarity of 1413+135 with the BL Lac objects is that it probably lies in the centre of an elliptical galaxy ($z = 0.26$). A study of the environment in which red QSOs, like 1413+135, exist is aided by the exceptionally steep nonthermal spectrum, which does not interfere with the identification of galactic spectral features.

One of the most striking features of the composite nonthermal spectrum (Fig. 1) is that the X-ray data cannot be explained as an extrapolation of the IR data to higher frequencies; any smoothly extrapolated curve falls orders of magnitude below the observed X-ray flux. The radio–optical continuum is usually interpreted as synchrotron radiation produced by relativistic electrons. High polarization at 2 μm is consistent with this interpretation. We suggest that the X-ray emission, which is clearly not an extension of the radio optical emission, is inverse Compton radiation.

The abrupt steepening in the spectrum near 5 μm from $\alpha \simeq 0.8$ (ref. 4) to $\alpha \simeq 3$ cannot be achieved by any evolutionary model[19]. The sharpest spectral cutoff occurs for an electron distribution which ends abruptly at some energy, such as

$$N_e = N_0\gamma^{-n} \qquad \gamma < \gamma_2$$
$$N_e = 0 \qquad \gamma > \gamma_2 \qquad (1)$$

The general solution for the spectrum emitted by this electron distribution[20] has been solved here for several values of n (equation (1)). These solutions describe a simple power law of slope α for frequencies below a critical frequency ν_2 ($\alpha = (n-1)/2$ in this region), while the spectrum steepens very sharply above ν_2, eventually becoming exponential for $\nu \gg \nu_2$ ($\nu^{0.5}\exp(-\nu/\nu_2)$). An important feature of these solutions is that their shape is insensitive to the value of n (or α) at high frequencies ($\nu > \nu_2$). As demonstrated in Fig. 1, the solutions fit the IR data extremely well. The range of critical frequencies ν_2, which are determined for each fit (Table 3) corresponds to the wavelength range 2.6–3.8 μm ($\alpha = 0.3$–1.5).

The sharpness of the spectral cutoff forces us to make two strong qualitative conclusions. First, the electron distribution in the emitting region terminates abruptly at some energy. Second, the magnetic field is fairly uniform in the IR emitting region. More precisely, magnetic fields above some critical field strength either do not exist, or they occupy an insignificant volume in the emitting region in which the IR photons are produced. Furthermore, if the relativistic electrons retain their velocity distribution between the emitting region and the region in which they were created, then the electron acceleration process is not diffusive in energy.

The size of the emitting region, its magnetic field, as well as the energy cutoff corresponding to ν_2 can be determined within the framework of a theoretical model. We have chosen the homogeneous synchrotron-self-Compton model of Jones *et al.*[21,22] with the added feature that the emitting region may have a bulk velocity towards the observer in the quasar rest frame (that is, a special case of relativistic motion is allowed). Equations (33) and (37) of Jones *et al.*[22] were solved, with various correction factors set to unity (that is $(\varepsilon_{sc}G_{sc})^{0.5}f^{-\alpha-1} = 1$). To apply this model, one must know the frequency and flux at which the IR emitting region becomes optically thick (ν_b and F_b) as well as the shape of the electron distribution (n or α). Only two of these quantities are independent.

Our simultaneous observations are consistent only with the models for which $1.5 \geq \alpha \geq 0.3$. If non-simultaneous observations[4] can be used to estimate α and the turnover frequency, $\alpha \simeq 0.9$, and $\nu_b = 1.6 \times 10^{11}$ Hz (this defines a preferred model, no. 3). To obtain model parameters, we fit the calculated spectrum to the IR spectrum, and for each value of α, we find a value for F_b consistent with our spectrum or that of Beichman *et al.*[4]. The model equations are solved assuming that the X rays arise from the inverse Compton process, and with the condition that the size determined from temporal flux variation equals the size determined with the synchrotron-self-Compton model.

The temporal flux variations of 24–26 January 1980 at 2.2 μm place an upper limit on the size of the emitting region (for an optically thin emitting region, $\beta \simeq 2$):

$$s \leq \beta c|F_\nu\, \mathrm{d}t/\mathrm{d}F_\nu|/(1+z') = 8\times 10^{-3}/(1+z')\ \mathrm{pc} \qquad (2)$$

where z' includes both cosmological expansion plus the motion of the emitting region with respect to the quasar rest frame. The model solutions are presented in Table 3, where $B \sin\theta_0$ is the magnetic field (θ_0 is the mean angle the magnetic field makes with our line-of-sight), d is the radius of the emitting region, θ is

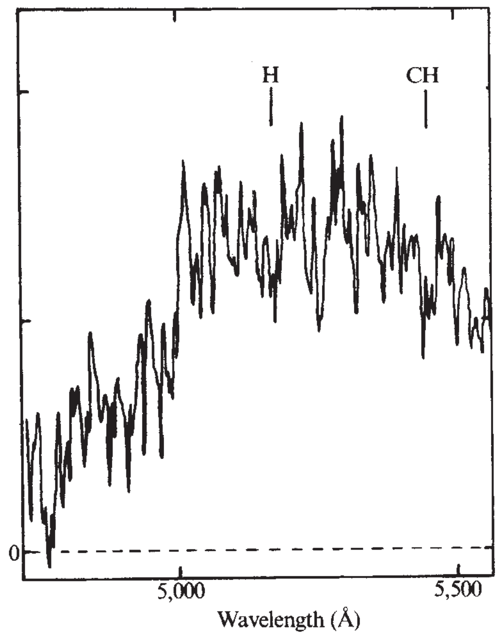

Fig. 3 The clear break at 5,000 Å in the galaxy around 1413+135 is interpreted as the H and K break redshifted by $z = 0.26$. The *Hδ* and CH absorption features, denoted here by H and CH, appear weakly in this spectrum. The spectral resolution is ~10 Å, and the observations were made through a 2.5 arc s round aperture.

Table 3 Theoretical model results

Model no.	α	ν_2 (Hz)	ν_b (Hz)	F_b (Jy)	θ (ms)	$B \sin\theta_0$ (G)	r (pc)	γ_2	Γ
1	0.4	7.8+13	2.2+10	2.0	1.1−1	8.2+0	5.0−2	6.1+2	4.0
2	0.6	7.9+13	6.6+10	4.0	6.7−2	3.2+1	3.9−2	3.4+2	3.2
3	0.9	8.5+13	1.6+11	7.0	4.3−2	6.1+1	3.1−2	2.9+2	2.6
4	0.9	8.5+13	1.4+12	1.0	4.6−3	6.4+3	1.0−2	5.0+1	1.03
5	1.5	11.5+13	1.8+12	5.0	6.9−3	2.3+3	1.3−2	8.8+1	1.24

the angular size of the optically thin region one would observe, γ_2 is the cutoff energy of the electron spectrum, and Γ is the Lorentz factor which describes the motion of the emitting region with respect to the quasar rest frame. Because temporal flux variations may yield only a lower limit to the source size, we formally determine upper limits to $B \sin \theta_0$, θ and r, and lower limits for γ_2 and Γ. However, in the following discussion, we assume that the size determined from IR flux variations is a good measure of the size of the emitting region (that is equation (2) is an equality).

Several of these models may be ruled out because the results violate fundamental physical considerations. The electrons must be energetic enough to scatter synchrotron photons to X-ray energies; this places the limit $\gamma_2 > 10^2$. Therefore, all models with $\alpha > 1.3$ or $\nu_b > 10^{12}$ must be eliminated from consideration. The difference in the values of B, r, γ_2 and Γ between the preferred model (no. 3) and the models allowed by our data (nos 1, 2) is not large. Note that this is the first time that γ_2 ($\sim$300) has been calculated.

The derived values for the magnetic field (60 G) and the source size ($\sim$0.03 pc) differ significantly from the canonical values derived for other sources (typically several microgauss and 0.1–100 pc (ref. 22). An independent argument in support of this field strength is that if the IR flux variation is attributable to electrons losing their energy in the time defined by temporal flux variation, then $B \sin \theta_0 > 0.2$ G.

The finding that the emitting region is moving away from the quasar towards us at relativistic velocities is consistent with either a beam model or an expanding shell model for the emitting region. The value of Γ we derive ($\simeq$3) is similar to what other investigators estimate for BL Lac objects[16,22]

Beichman *et al.*[4], who used a model which does not allow for relativistic motion and does not use the X-ray flux as a measure of the inverse Compton radiation, obtain results similar to our own.

Conclusions

We have studied the radio, IR, optical and X-ray spectrum of the extremely red QSO 1413+135 and find: (1) It is embedded in a luminous galaxy at a redshift of $z = 0.26 \pm 0.01$. (2) It is very closely related to BL Lac-type sources, as shown by its pattern of variability in the radio and IR, by its strong IR polarization and by its lack of emission lines. (3) The radio spectrum, which is always inverted, is subject to large outbursts that occur over a period of a few months. While these outbursts occur simultaneously at 8 and 14.5 GHz, the greatest amplitude occurs at 14.5 GHz. The observations exclude the simple expanding source model. (4) Its nonthermal spectrum steepens abruptly near 5 μm, requiring that the electron energy distribution terminate sharply at some maximum energy (Lorentz factor 10^2–10^3) and that the magnetic field is uniform within the IR emitting region. (5) The X-ray data lie far above an extrapolation of the IR spectrum to high frequencies. We suggest that the X-ray emission is produced by the inverse Compton process. (6) The magnetic field in the source is probably >1 G, and the emitting region ($\sim$0.03 pc) must be moving towards us with a Lorentz factor between 1.5 and 4.

We thank C. Beichman for useful conversations. H.D.A., M.F.A. and P.E.H. thank the staff of the University of Michigan Radio Observatory for assistance and the NSF for their support. M.J.L. and G.H.R. thank B.T. Soifer for data prior to publication, and J.C. Kemp and R. J. Weymann for assistance with instrumentation. This work was supported by the NSF. Part of this research used the Multiple Mirror Telescope Observatory, a joint facility of the University of Arizona and the Smithsonian Institution. J.N.B., A.E.G. and P.J.H. thank Knox Long, Fred Seward and G. Fabbiano for help in obtaining and reducing the X-ray data. The Einstein guest observer programmes were supported by NASA grants. Finally we thank H. Spinrad for valuable criticisms.

Received 11 June; accepted 14 August 1981.

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Expression of a human gene for interferon in yeast

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A DNA sequence coding for mature human leukocyte interferon D (LeIF-D) was linked with DNA fragments of the 5'-flanking sequences of the Saccharomyces cerevisiae *(yeast) alcohol dehydrogenase I gene in a plasmid capable of autonomous replication and selection in both yeast and* Escherichia coli. *Yeast cells transformed by these plasmids synthesize up to* 1×10^6 *molecules of biologically active LeIF-D per cell.*

In addition to its usefulness as a model for studying eukaryotic cellular processes, the yeast *Saccharomyces cerevisiae* is a suitable host cell in gene expression experiments. The yeast transformation procedure[1,2] allows both the reintroduction of cloned and *in vitro* mutated yeast DNA sequences (to map functional sites) and the direct cloning of yeast genes by functional complementation of defective mutants[3] (for review see ref. 4).

Similarly, a particular genomic sequence from another eukaryotic organism might be isolated by complementation of defined yeast mutants affecting genes common to both organisms. While this approach has been successful for a *Drosophila* gene corresponding to the yeast *ADE*8 locus,

0028–0836/81/440717—06$01.00