is puzzled by the solid cementing. Many of the islands we visited have terraces and flat tops of solid rock, but none of the rock formations proved to represent coral reefs grown in place; all corals appeared to have been thrown up by waves during violent storms and later incorporated into various types of beach rock. The same interpretation had been made for other islands (*11*). This type of beach rock or rubble rock forms very rapidly in the tropics; we found many relics of World War II incorporated in some outcrops. On Jaluit Atoll we counted as many as four layers, at least three representing deposits during great storms, lying one atop the other, each grading from coarse rubble below to somewhat finer above, with weathered zones between (Fig. 2). The size of some of the corals in these rubble rocks is amazingly large, and one can easily see why they have been mistaken for growing reefs—especially when some of the blocks have landed right-side-up after transportation by the waves.

Indications of beveling by erosion of some of the beach rock, up to about the high level of spring tide, may possibly indicate slightly higher stands. Moreover, the preliminary carbon-14 dates from this rubble range only from 1890 to 4500 years ago. Some flat-topped ridges of beach rock were rather hard to equate with present reef flats, but none carry atop them corals in position of growth; furthermore, the flat tops may reflect firm cementation up to the level of high tide and erosion by storm waves above that level.

The dates of 1890 to 4500 years ago, with something of a cluster around 2500 to 3000 years, indicate a period when the sea, according to most recent investigators (*2*), stood quite close to the present level. The fact that these preliminary dates include none younger than 1890 years ago may have some significance, but deposits by older storms have had more time to be firmly cemented. Reasons for our failure to find younger firmly cemented terraces (apart from the contemporary reef flats) are not clear. Relative subsidence causes coral growth to flourish. If the rate of rise of sea level slowed or if the level dropped slightly between 2000 and 3000 years ago, before the final rise to the present level, more coral material then became available for erosion and incorporation into storm beaches. Alternatively, storms may have been more intense during the period that includes the cluster of dates.

We do not wish to imply that our investigation has solved for the Pacific the problem of sea level. Admittedly our evidence is only negative, and there are vast tracts of relatively stable island archipelagoes where our results should be checked. Particularly valuable would be probes of the estuaries on the high islands of these groups, searching for peat deposits below sea level that may provide more positive evidence of the history of sea level. Results of our studies of this sort are not yet ready, partly because we are waiting for this material to be dated. Major unsolved problems emphasized by our investigations include the cluster of dates, from flat-topped cemented rubble terraces, between 2500 and 3000 years ago, and the firm cementation of this rubble up to approximately the present level of high tide.

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Emission-Line Variability and Distance of Quasars

Abstract. *The radius of the line-emitting region in quasars is larger than 1 parsec for the cosmological hypothesis and smaller than 1 parsec for the local hypothesis. Variability in emission lines has been reported but not proved beyond doubt. Its time scale would be a direct observational indicator of this radius and would add an important element to the discussion of the origin of quasars. Objects that are variable in their optical continuum seem to be the most promising ones to look at for line variations, and they should be observed spectroscopically at regular intervals.*

Greenstein and Schmidt (*1*) have estimated the radius of the line-emitting regions in quasars under the assumption that the cosmological hypothesis holds, that is, that the red shifts are caused by the expansion of the universe. They found a few tens of light-years for the radius of 3C 48 and a few light-years for 3C 273. Oke (*2*), however, has argued that the radius of 3C 273 might be larger. In the present report we want to estimate a minimum radius by a somewhat simpler method, and to point out implications of this determination for the question of local (*3*) or cosmological origin of quasars.

Two conditions must hold if forbidden lines are emitted by a gas (*4*). First, the electron density must be so low that there occurs no appreciable depopulation, by electron collisions, of a metastable state which has been filled up from the ground state by electron collisions or from higher states by allowed transitions. This condition was used by Greenstein and Schmidt to calculate the number of forbidden transitions per cubic centimeter per second, and, from the observed luminosity, the radius of the emitting region. Second, the excitation from the metastable to higher states by absorption of radiation must not occur too often. This means that the radiation density must be small. From this condition, we shall derive a minimum radius (r_{min}) of the inner edge of the region where the forbidden lines originate.

We assume this region to be spherically symmetric with respect to the very small region ($< 10^{17}$ cm) of continuum emission. The latter region is thought to include the source of the energy that is radiated in the emission lines (*5*). Unless the energy output of this source is much larger than that in the optical continuum, the assumption of crude spherical symmetry seems to be a necessary one, and follows from the fact that an appreciable part of the total luminosity (of the order of 10 percent) is radiated in the emission lines. This obviously implies a rather effective absorption of the exciting energy which can best be accounted for by a more-or-less closed envelope unless very complex quasar models are considered.

The number of excitations from the metastable state m to a higher normal state n by absorption of radiation is given by

$$N_1 = n_m A_{nm} F_{nm} g_n / g_m \quad (1)$$

where n_m is the number of atoms in the state m, A_{nm} is the Einstein probability coefficient, g_n and g_m are the statistical weights of the states, and

$$F_{nm} = U_{nm} c^3/8\pi h\nu_{nm}^3 \quad (2)$$

U_{nm} is the radiation density (erg/cm^3 per c/sec) at the radiation frequency ν_{nm} of the transition (*6*), and c is the velocity of light.

The forbidden line is about as strong as allowed lines if N_1 is smaller than the number of forbidden transitions into a lower state 0 which is given by

$$N_2 = n_m A_{m0} \quad (3)$$

An allowed transition probability is of the order of 10^8 sec^{-1}, while for the [O III] λ 5007 line, for example, the forbidden transition probability is about 2×10^{-2} sec^{-1}. The radiation density well outside the region of continuous emission is

$$U_{nm} = L_{nm}/8\pi r^2 c \quad (4)$$

where r is the distance from the center, and L_{nm} (erg/sec per c/sec) is the luminosity at the transition frequency ν_{nm}. For the [O III] line, $\nu_{nm} \approx 3 \times 10^{15}$ sec^{-1}, corresponding to a wavelength of 1000 Å or to a transition energy of 10 ev. We can now estimate L_{nm} from the known luminosity in the extreme ultraviolet, which is of the order of 10^{46} erg/sec for the range 1000 to 3000 Å, that is a range of 2×10^{15} c/sec. This gives $L_{mn} = 5 \times 10^{30}$ erg/sec per c/sec. Inserting this into Eq. 2, we find $F_{nm} \approx 10^{29}\ r^{-2}$. From the condition $N_1/N_2 < 1$ it follows now that

$$r > r_{min} = 3 \times 10^{19}\ \text{cm} = 10\ \text{parsecs} \quad (5)$$

The very crude approximation used leaves, however, a large uncertainty in the value of r_{min} which may amount to a factor of 10 or so. If r_{min} should turn out to be much larger than the effective radius of the emitting region as determined by the calculation of Greenstein and Schmidt, the emission would take place only in a very thin shell. This seems not very probable. On the other hand, no objection can be raised against a minimum radius (r_{min}) smaller than the effective radius of the emitting region. Apparently our estimate is not in contradiction to the radius determination of Greenstein and Schmidt, and indicates that the actual radius r is not much larger than r_{min}. It holds, approximately, for all the forbidden lines. However, it gives no direct indication where the other lines (from allowed transitions) are emitted.

The existence of a minimum radius strongly restricts the possible variability of the strength, the form, or the medium wavelength of emission lines. If we observe variability of smaller time scale than r_{min}/c, the estimate of r_{min} cannot be correct. We have to reduce our estimate of L_{nm} which depends on the assumed distance d of the quasars. We have L_{nm} (local) $=$ L_{nm} (cosmol.) $\times$ [d^2 (local) / d^2 (cosmol.)]. It can be seen from Eq. 4 that r_{min} is proportional to d. The local hypothesis reduces the distances by a factor of 100 or more, indicating radii r not larger than about 1 parsec.

Rapid variability, in a time scale of months or less, would be a strong argument for the hypothesis of local origin of quasars. On the other hand, if we find only slow changes or no variability at all, this would favor the cosmological hypothesis. This case, however, is not as strong as the foregoing. The analogy to the planetary nebulas implies that the energy radiated in emission lines comes from the Lyman-continuum range of the continuous radiation. If this radiation changes rapidly, the emission lines should vary with a time scale of the order of r/c. But we cannot observe the continuous radiation shortward of the Lyman limit, and we do not know whether it varies as much as the continuum does at other wavelengths. Furthermore, the energy for the line emission might come from another source, and the radiation stored in the line-emitting region might be a very effective buffer to all changes of emission lines.

Rapid line variations have been reported for 3C 345 by Burbidge and Burbidge (*7*) and indications for this effect in the same object have been reported by Wampler (*8*). However, as was pointed out by G. Burbidge (*9*), the case is not so clear as it seemed at first, and there could be the possibility that the observed effect is not a real line variation but simply due to a change in the underlying continuum. In 3C 446 where rapid and heavy changes of the continuum have been reported (*10*) in 1966, the emission lines seem to have remained constant during several months after the outburst (*2, 11*).

Those objects that are strongly variable in their optical continuum seem to be the most promising ones to look at for line variations. A careful reduction of spectra or tracings taken two or three times a year might yield, in a relatively short time, definite proof of rapid line variations or arguments for the absence of this effect. A result of this kind would make an essential contribution to the discussion on the origin of quasars.

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