545 nm bands, seems to be the sulphur vacancy. The other, which causes the 355 nm absorption, was not identified. The presence of halogen or aluminium impurities also affected the spectra observed.

It therefore seems that illumination-drifted filters might be restored to their original condition by suitable illumination and/or heat treatment. Furthermore, it may be possible, by controlling the impurity content of the zinc sulphide, to make interference filters whose passband does not drift under illumination.

Crack theory developed

from Peter J. Smith

THE dilatancy model for earthquake precursors is one which in general terms attracts wide support. But as O'Connell and Budiansky (*J. Geophys. Res.*, **79**, 5412; 1974) point out, there are disagreements over detail which reveal that understanding is far from complete. For example, Nur (*Bull. seismol. Soc. Am.*, **62**, 1217; 1972) proposed that the precursory decrease in P wave–S wave velocity ratio (V_P/V_S) is due to the opening of new dry cracks in the focal zone of an earthquake, whereas Whitcomb *et al.* (*Science*, **180**, 632; 1973) noted that vaporising the fluid in saturated cracks would have the same effect. Perhaps it would be wrong to describe this as a disagreement, since it is doubtful whether either party would man the barricades to support their respective viewpoints; suffice it to say that here we have two possible mechanisms for the same phenomenon and that it is necessary to determine which, if either (and if not both), actually obtains.

What does seem to be agreed by most people is that the elastic responses of rocks in an earthquake zone are critically dependent upon the presence of internal cracks and pores and whether they are wet or dry. Yet even here the dilatancy models currently available may be incorrect in detail. As O'Connell and Budiansky again point out, current theoretical analyses of the effect of cracks on the elastic properties of solids apply only to systems in which the cracks are assumed to be so far apart that the effect of each crack on the properties of the uncracked material may be determined independently. This was the basis upon which Walsh (*J. geophys. Res.*, **74**, 4333; 1969), for example, assessed the influence of both dry and saturated cracks; and his analysis was derived, in turn, from the earlier work of Wu (*Int. J. Solids Struct.*, **2**, 1; 1966) and Eshelby (*Proc. R. Soc.*, **A241**, 376; 1957). Actual crack densities in rocks have seldom been measured or estimated. So are dilatancy models involving low crack densities really valid?

To find out, O'Connell and Budiansky have carried out a new theoretical analysis which puts no initial restriction on the crack density and thus takes into account interactions between cracks. This freedom turns out to be critical. The model itself consists of a solid containing very thin randomly oriented ellipsoidal cracks which may be wholly dry, wholly saturated or a mixture of both. When the elastic properties predicted from the model are compared with the experimental data obtained by Nur and Simmons (*Earth planet. Sci. Lett.*, **7**, 183; 1969), who measured wave velocities in both dry and saturated rock samples at various pressures up to 3 kbar, it becomes quite clear that consistency can only be achieved by relatively high crack densities. For example, at zero pressure dry Westerly granite has a crack density of 0.25, which corresponds to one crack of diameter 1.2 units per unit volume (for example, one crack with a diameter of 1.2 mm mm^{-3}). The corresponding figures for other dry rocks measured by Nur and Simmons range from 0.15 to 0.6, while in its wet state the Casco granite has a crack density as high as 0.7 (dry 0.4). Thus, all the rocks are extensively cracked and hence not strictly amenable to any theoretical treatment which presumes dilute crack concentrations.

A similar comparison is possible between the characteristics of the O'Connell–Budiansky model and the premonitory behaviour of the rocks in the region of the San Fernando earthquake of 1971—with equally interesting results. As Whitcomb *et al.* have reported, the seismic velocity ratio V_P/V_S decreased from its normal value some 3–4 years before the San Fernando event and then gradually increased to its initial value just before the shock occurred. The original discovery of this effect was based on small earthquakes which preceded the main San Fernando shock in what was later seen to be the aftershock area and which were recorded at two stations on the same side of the aftershock zone. Subsequent work has shown that a similar result is obtained for small earthquakes occurring well outside the limits of the aftershock area but measured at two stations which have the aftershock zone between them. In other words, precursory changes in V_P/V_S are observed irrespective of whether the waves used to measure V_P and V_S pass through the main shock's epicentral zone or not.

In terms of the O'Connell–Budiansky model, however, the gross similarity in V_P/V_S behaviour does not entirely extend to the physical mechanism behind the variations. Outside the San Fernando epicentral region (original data recorded at stations on the same side of the region), the crack density before the V_P/V_S decrease lay in the range 0.2–0.3 and the cracks were predominantly saturated. Then during the V_P/V_S decrease in 1967 the crack density decreased marginally and the fluid in the cracks vaporised, which is consistent with the interpretation made originally by Whitcomb *et al.* But during the subsequent increase in V_P/V_S the crack density decreased much more noticeably to 0.15 and the cracks resaturated. This reduction in crack density in inconsistent with increased dilatancy upon resaturation, and implies instead a relaxation of strain which allows some cracks to close completely and the rest to relax sufficiently to eliminate the vapour

Getting closer to prediction

from Peter J. Smith

THE United States Geological Survey claims that "significant progress" was made towards earthquake prediction when scientists at the National Center for Earthquake Research in California managed to anticipate a moderate shock which took place on November 28 last year. This event, which had a magnitude of 5.2, occurred between the San Andreas and Calaveras faults about 16 km north of Hollister, California.

Prediction was based largely on precursory deformation of the Earth's crust and changes in the magnetic field. Crustal tilting was first observed about 4 weeks before the earthquake at two locations near what was to be the epicentre. But a "dramatic anomaly" in the geomagnetic field in the epicentral region was spotted about 6 weeks ahead. Later analysis of recorded seismic data showed that premonitory variations in seismic wave velocity had also occurred.

According to the survey's director, Dr V. E. McKelvey, this is the first time that such a variety of precursory phenomena has been observed for a single earthquake in the United States. He warned, however, that this success should not be taken to imply that routine prediction for public safety planning is now possible. Significantly, he also pointed out that much still needs to be learned about how successful prediction could be used most effectively in reducing hazards.

phase within them. Inside the epicentral region (later data recorded at stations on opposite sides of the region), the pre-1967 crack density was slightly higher than outside but again the cracks were mostly saturated. And again the V_P/V_S decrease was accompanied by a decrease, albeit rather more marked, in crack density. But thereafter the picture changed. The subsequent increase in V_P/V_S was again related to resaturation but was now accompanied by an increase in crack density.

In summary, then, there are significant differences in the precursory processes inside and outside the immediate epicentral zone. Close to the main shock area the sequence is dilatancy–resaturation–dilatancy, whereas further away the sequence becomes dilatancy–resaturation–relaxation. Extensive cracking is common to both regions, however, and extends over a much wider zone than some workers have previously supposed. And again contrary to some previous views, the observed decrease in V_P/V_S is not due to the formation of new cracks but to a change from saturated to dry cracks. Indeed, changes in the saturation state of the cracks are apparently more important on the whole than changes in crack numbers.

Opening up the Universe

from P. C. W. Davies

MOST cosmologists now accept that the Universe began with a bang. But how will it end? The question has been of long-standing interest to both theologians and scientists, though the former have enjoyed greater success in producing answers. In recent months, however, evidence has been accumulating from diverse astronomical sources which consistently points toward a definite scenario for the future of the Universe. Although there is no question of a unanimous verdict at this stage, a movement of opinion among the pundits is becoming perceptible.

All discussion of this matter takes place within the context of the standard model for the Universe. In this standard model, the Universe moves in compliance with Einstein's general theory of relativity. This motion is visible to us as a general pattern of expansion, and because of the apparent large-scale homogeneity and isotropy, this expansion is assumed to be everywhere uniform.

If Einstein's equations are solved for such a uniform model universe they yield a two-parameter family of motions. All of these solutions predict that the expansion began a few billion years ago, when the Universe was in a very dense condition. The onset of the expansion, expected to be very hot, is the big bang. The past history of the Universe is therefore, in broad outline, fairly unambiguous according to this theory.

As regards the future motion of the cosmos, all the solutions predict a gradual decrease in the expansion rate. Where they differ is in whether the decrease is strong enough to arrest the expansion and bring about recontraction, with the Universe falling back on itself to end up in a bang much like the one from which it originated. The alternative is for the expansion to continue for ever, with the Universe slowly sinking into thermodynamic equilibrium, after which little of significance will occur.

In principle it is easy to decide between these alternatives. Observations of the rate of recession of distant galaxies, seen as they were in the remote past, should indicate how the expansion rate has slowed since then. Alternatively, measurements of the present energy density in the Universe enables the gravitating effect to be calenable the gravitating effect to be calanswer (through the general theory of relativity) as to how vigorously this gravitation is slowing the Universe down.

In practice, both types of observation are difficult to perform and complicated by many contentious side-issues. Now a paper has appeared in the *Astrophysical Journal* (**194**, 543; 1975) by Gott and Gunn from Caltech and Schramm and Tinsley from the University of Texas in which many of the observations and their theoretical ramifications are examined in detail. Gott *et al.* opt for an ever-expanding (or open) universe. Some of the arguments they use were presented by Gunn at the Seventh Texas Symposium on Relativistic Astrophysics (see the report from John Faulkner, *Nature*, **253**, 231; 1975).

The authors parameterise their models in terms of the Hubble parameter H_0 (expansion rate at present epoch) and Ω, the ratio of the observed density of energy to the critical density required to collapse the Universe. For an ever expanding Universe, $\Omega \leqslant 1$. Their figure 1 shows the constraints obtained in their paper on these parameters.

Although H_0 may be measured directly ($30 < H_0 < 120$ km s^{-1} Mpc^{-1}) the age of the Universe, t_0 (8 to 18 billion years), is a more severe constraint. A direct estimation of the deceleration is complicated by evolutionary effects in both galaxies and QSOs, which tend to result in an overestimation of the deceleration parameter, q_0 ($=\Omega/2$). To play safe an upper limit of 2 is placed on this parameter.

In contrast, the density (Ω) measurements tend to be underestimates, first because we only see the luminous matter in the Universe (stars, gas) and second because energy density may reside in the form of very low energy radiation (gravitons, neutrinos). Various methods for estimating Ω are critically described in the paper. Three independent estimates of the relative density of galaxies alone (denoted Ω^*) are used to obtain a value 0.05 ± 0.01, and various arguments reviewed as to why any intergalactic matter would not be sufficient to give $\Omega > 1$.

In addition, a mention is made of recent theoretical work on the production of deuterium by nucleosynthesis in the hot big bang. The fraction of deuterium produced (D/H or ratio of deuterium to hydrogen) turns out to be very sensitive to the present energy density of the Universe. Using the results of measurements of galactic deuterium abundance, it is concluded that remarkably narrow ranges of Ω and H_0 are permitted in which $0.05 < \Omega < 0.09$ and $49 < H_0 < 65$ km s^{-1} Mpc^{-1}, predicting an ever-expanding Universe by a wide margin. The possibility of galactic deuterium production and nonstandard big bang physics is briefly reviewed.

The authors conclude that the density of the Universe is low, $\Omega \sim 0.06 \pm 0.02$, and a recontraction is ruled out. The most persuasive part of their argument is the fact that an ever-expanding Universe follows consistently from all the different sources of data, whereas to produce a recontracting model, a number of *ad hoc* assumptions are necessary. It is always possible to invoke exotic processes in the big bang, or to conjecture that most of the mass of the Universe is in the form of undetectable gravitational waves or black holes. But such conjectures are extremely hard to falsify with current technology, and seem somewhat contrived.

If Gott *et al.* are right, then instead of the Universe going out in a blaze of glory by recontraction, collapse and final cremation, it is doomed to everlasting frozen stagnation, when the stars go out in a few dozen billion years.

Erratum

IN the article "Chilling Statistics on Cyprus" by Peter J. Smith (*Nature*, **253**, 500; 1975) magnetic vectors are mentioned in the last sentence of the fourth paragraph. This is incorrect and the sentence should read: "In other words, on each side of the intrusion zone the chilled margins will all lie in the same direction (they will all be 'one way') and the degree of 'one way chilling' will be 100%."