Resolving the mystery of the quasars?

These controversial objects, which appear to some to violate the known laws of physics, may prove to be highly condensed, rotating centers of extremely distant galaxies.

Philip Morrison

The quasar continues to rank both as one of the most baffling objects in the universe and one most capable of inspiring heated argument. But it is going on 10 years since we first became aware of the unusual properties of quasars and, although no one is foolhardy enough to claim to have solved the mystery, we have over this time accumulated a fair amount of information about quasars. My thesis is that the available data can be fitted by a relatively conventional picture of quasars as the condensed central cores of galaxies occuring at a certain point in their evolution. Although others share this view, a number of my colleagues and critics in the business of quasar theories do not. I ask their indulgence for this simplified and undocumented presentation of physical arguments and encourage them to seek —if they have not already used up— equal time.

It is important to realize that, in terms of its optical image, the famous, enigmatic quasar is an uninteresting, uninspiring and commonplace object, looked at purely observationally. Only when you impute to it some theoretical nature do you then grasp what a remarkable object it is. This paradox is one of the fundamental points of the whole discussion about quasars. Figure 1 shows Palomar Sky Survey enlargements, in which some quasars were marked by Margaret Burbidge years ago. When you look at these plates, you see that the images identified by the reference marks are rather inconspicuous, showing no detail of any kind. They are images wholly determined by the imperfections of instrument, plate and atmosphere. You see plenty of other images bigger and better all around. So why single these out? Obviously, there must be some reason not present on the face of the image.

Even the most fascinating quasar, 3C 273, the closest one and one that shows some elements of structure, really has to be argued out quite a lot before it begins to look like a very important object.

We have identified about 200 of these uninspiring looking objects which we call quasars. The sample was obtained with procedures random enough that on the whole we are pretty sure, unless we are very unlucky, that there must be in the sky 100 000 to a million such objects down to about the 20th magnitude.

Uniqueness of quasars

To see in what way the quasars are unusual let us classify the kinds of objects we see in the sky. First, consider whether the image is unresolved or resolved. *Unresolved* means an image whose physical dimension on the plates is fixed by instrumental, atmospheric and detector qualities alone. As you know, this is true for all optical images less than half a second of subtended angle; in most instances one second is the best you can do.

The images that we see in figure 1 are all around one second of arc. All of them are primarily determined by the atmospheric seeing. There is no structure visible. We see the four arms of the diffraction pattern coming from the spider in the camera, quite characteristic in bright objects; we recognize at once it has nothing to do with the object. This is true for all optical images until they get bigger than a second of arc.

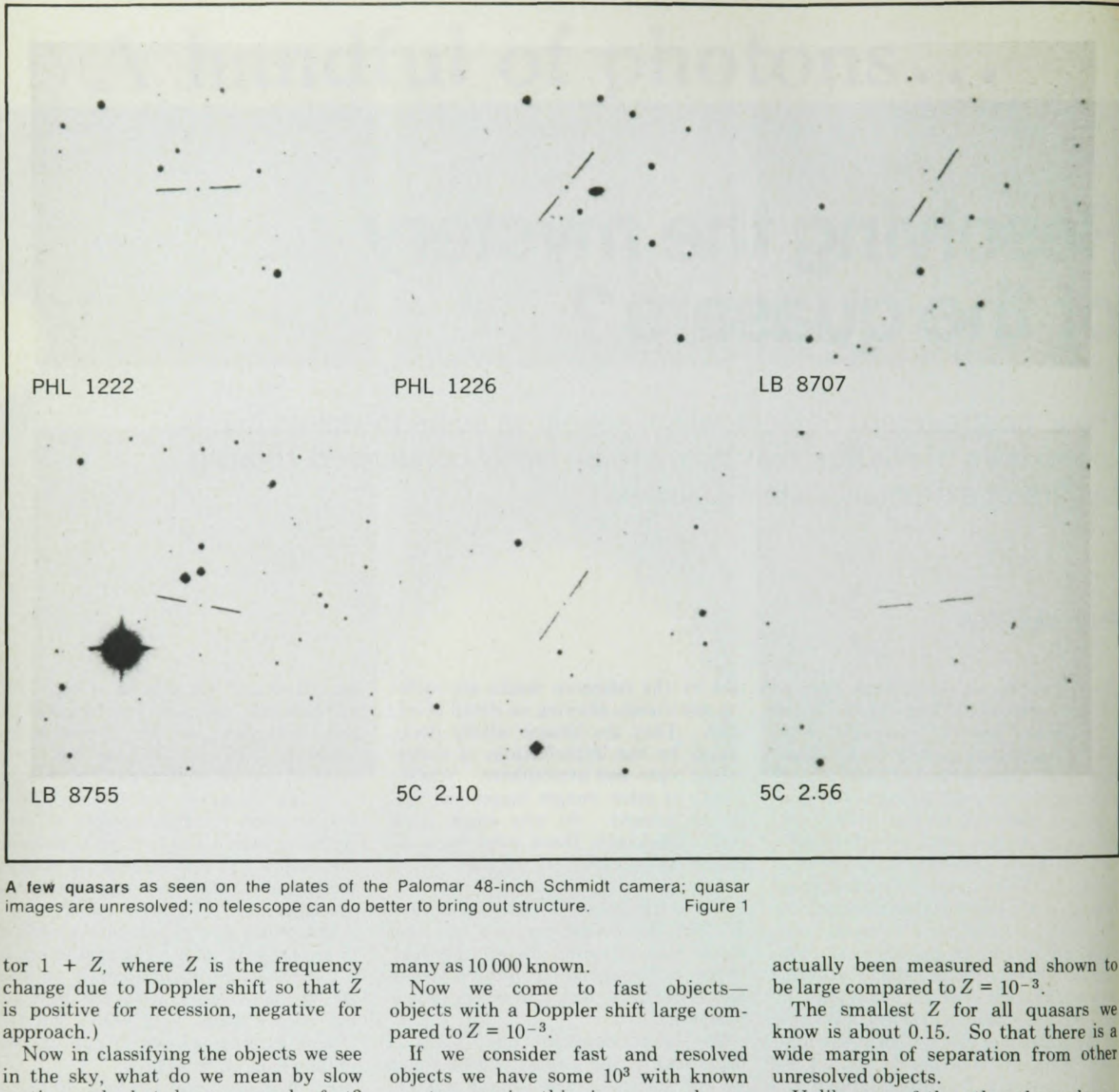
But recall what linear size a second of arc projects into. A second of arc is a 200 000th part of a radian; if we look 200 000 light years away the best we can resolve is one light year. But the closest external galaxy to ours is two million light years away.

So by the time we look to large extragalactic distances, we are not able to see linear distances smaller than hundreds or even thousands of light years. That's the best that optical telescopes can do.

Using one second of arc as a dividing line, we can classify objects as unresolved or resolved. All objects bigger than one second of arc have an intrinsic structure, a shape; they look like spirals, like fluffy nebulae, they look like crabs or pineapples or whatever it is; we say they are resolved.

Now the second classification category we want to consider is whether the objects are moving slow or fast. We assume that an object's radial speed is given by the Doppler shift we observe in its spectral lines. (The observed frequency is usually given as the reference frequency divided by the fac-

Philip Morrison is a professor of physics at the Massachusetts Institute of Technology.



A few quasars as seen on the plates of the Palomar 48-inch Schmidt camera; quasar images are unresolved; no telescope can do better to bring out structure. Figure 1

tor $1 + Z$, where Z is the frequency change due to Doppler shift so that Z is positive for recession, negative for approach.)

Now in classifying the objects we see in the sky, what do we mean by slow motion and what do we mean by fast? Let us set up an arbitrary dividing line of $Z = 10^{-3}$, which turns out to be a very reasonable point of division. A Z of this size corresponds to about 300 kilometers per second in velocity, $Z = v/c \ll 1$.

Make up a four-fold table: slow or fast, resolved or unresolved, the two criteria yield 4 classes. In the slow and unresolved bin we see some 100 000 stars—those objects that, in fact, we ordinarily call stars. Most of them we believe really are stars because we see so many that we understand pretty well the nature of the spectrum and many other phenomena, and therefore we can really assert these are stars.

The slow and resolved objects are mostly seen to be nebulae and star clusters, within our own galaxy or a very few others. Maybe there are as many as 10 000 known.

Now we come to fast objects—objects with a Doppler shift large compared to $Z = 10^{-3}$.

If we consider fast and resolved objects we have some 10^3 with known spectra; again this is a sample we think drawn from a population probably greater than 10^8 or 10^9. These objects are the galaxies; the Hubble law and the whole study of extragalactic astronomy depends upon the fact that we've measured under a couple of thousand red shifts of resolved objects, whose forms resemble the spectra of conglomerates of stars.

Finally in the only remaining box we have the fast but unresolved objects—and these are *exclusively* quasars. An unresolved object with $Z \gg 10^{-3}$ is a working definition of the quasar, actually due to Maarten Schmidt, which almost all quasars satisfy. Our guess is that the population of these objects is 100 000 or a million. This is based only on a sample of 50–100 chosen at random from the sky for which the Doppler shift of the spectral lines has actually been measured and shown to be large compared to $Z = 10^{-3}$.

The smallest Z for all quasars we know is about 0.15. So that there is a wide margin of separation from other unresolved objects.

Unlike any of the other three classes of objects the physical nature of the quasars is essentially unknown. All we can say is that a quasar is an unresolved object having recognizable emission or absorption lines, or both, with a very large red shift, and no observable structure. (It is true that among the 200 quasars there are a handful that show some hint of optical structure such as wisps or jets.)

This is all we can say for sure about what the quasars are. And this leaves us with many questions. The whole issue is what is the real three-dimensional nature of these bodies? Are they close or far? Are they big or small? Are they old or new? They certainly don't look much like stars, yet they don't look dissimilar to stars *once* you forget the absolute value of the Z. But their Z's should indicate they're moving at extraordinary speed; it is impossible to understand how they could be in our galaxy. When they were first reported, that was not well understood; people thought maybe they were stars except that they couldn't make any sense out of the spectra. They compared the lines they were seeing with the reference books and came up with some strange inferences: lines of gadolinium three times ionized and so on.

Then Maarten Schmidt realized that, of the six lines in the bright quasar he was studying, four had the ratios of the Balmer series to an accuracy of two significant figures or better. At first he thought these were simply hydrogenic lines of some heavily ionized element but he couldn't find an atom that would make it work. Then he said, "Maybe the whole thing is just an enormous Doppler shift," and then everything fell into place.

Among the hundreds of thousands of stars, none had more than a hundredth part of this red shift. That is a big enough gap so that everybody could agree that here was quite a different kind of object.

In addition, most of the quasars first seen were also middling strong radio sources, although now we no longer take this as a necessary condition for quasarhood. But it adds more fuel to the fire, since almost no stars are known to be radio sources except at very low flux levels.

Let us return to the fast objects. Whereas all quasars have Z greater than 10^{-3} or even 10^{-1}, this is not true of all galaxies. Most known galaxies have Z's greater than 10^{-3} but less than 10^{-1}. Only a very few go far out, like 3C 295, to $Z = 0.46$ (figure 2). In any case the Z range for galaxies is from $Z \approx -0.001$ out to $Z \approx 1/2$. In comparison the range for quasars overlaps this range and extends to much larger values with the slowest quasar having $Z = 0.15$ and the fastest one $Z = 2.88$.

(There is a rumor that the galaxy speed record has been broken by two faint objects, one of which has $Z = 0.74$.)

We say to ourselves if the Z's we observe for the quasars are true, then these objects must be very far away indeed. The ones with $Z > 1$ are plainly much beyond the furthest galaxy. If you don't want to extrapolate our knowledge to such distances we can limit the discussion to the numerous quasars with Z around 1 (which is not very far from the $Z = 0.46$ of the fastest galaxy observed so far.) Unless there's some terrible injustice, the fact that one can recognize a galaxy out that far means that nothing cosmologically bizarre has come in. It looks as though we should be able to interpret the quasar Z's in the same way; that is the conventional view and I share it: it is right to apply the Hubble expansion to determine the distance of the quasars.

Properties of quasars

Once we make that assumption, we can go ahead and write down the properties that these objects have. First of all, and this is very important, the quasars are predominantly nonthermal sources. For example, a typical bright quasar has a spectrum of bright emission lines, a total emission-line intensity corresponding to say 10% of the total optical intensity of the object. The 90% left over is continuum. It is a blue polarized optical continuum, which is pretty surely recognized as being a typical synchrotron electron continuum, strongly polarized with a power-law intensity shape, $I \propto \nu^{-n}$ not at all like any black body you could fit. You can argue about a few exceptions, but the bulk of the quasars show nonthermal optical emission.

Second, quasars may often be variable in intensity, but they are not transient. We know that some of these objects have existed for at least a hundred years, from the old Harvard plates.

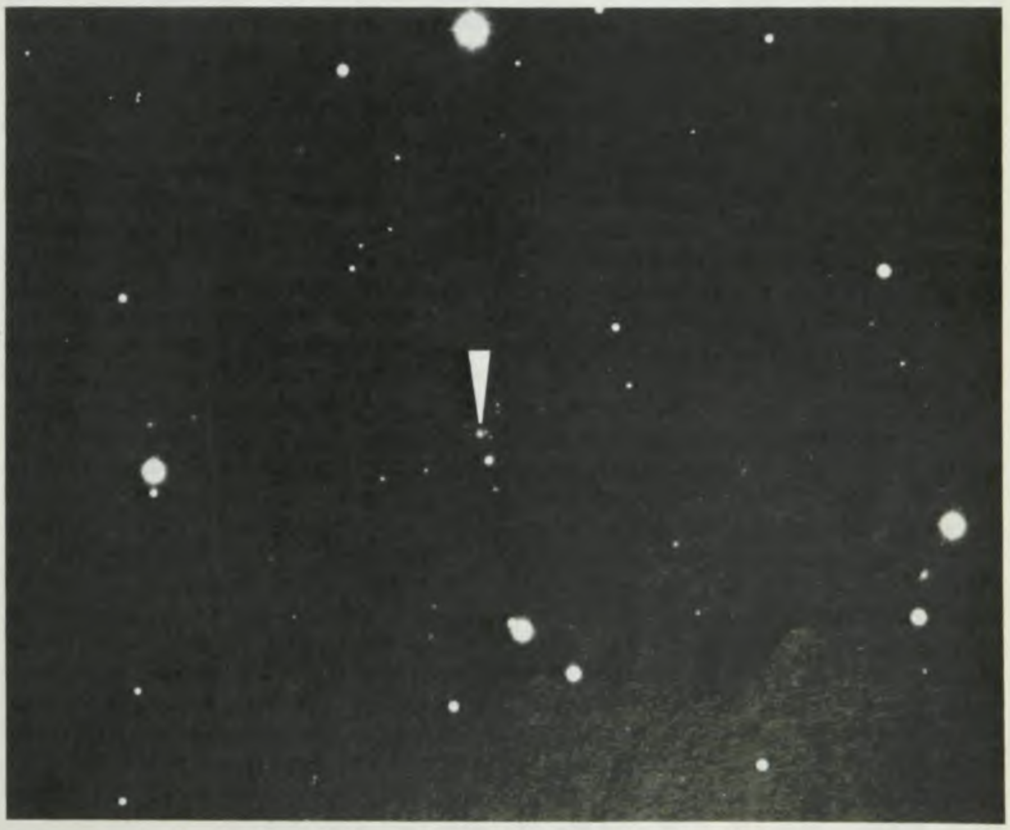
The other argument for a nontransient nature comes from the radio structure. The typical radio quasar has two quite extended radio lobes, invisible optically, and with dimensions of the order of 10^5–10^6 light years. Everyone tends to believe these double radio structures originated from the central disturbed object; if they did, then the material in those lobes must have taken some million years to move from the center to its present position.

On the other hand we observe that quasars are variable. Many quasars vary their *optical* intensity on a time scale which is characteristically a tenth of a year.

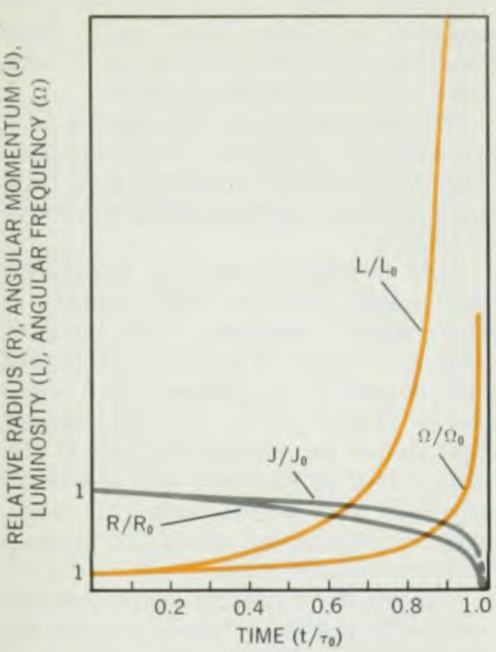
Now it follows from this variability that quasars must be very compact. If they weren't compact, they couldn't vary in a tenth of a year. No object can double in brightness in a time much smaller than the light-transit time across an appreciable part of the object. So we conclude that one-tenth of a light year is a characteristic maximum dimension for the optical heart of a bright variable quasar.

The structure of radio sources associated with quasars is known in some detail. We actually see a little cluster of radio clouds surrounding some quasars. But the smallest radio structure known is still of the order of a tenth of a light year to a light year in size, with larger structures all the way from a light year up to a million light years. Of course the million-light-year structures don't vary, and the ten-light-year structures vary a little bit in a year, and so on.

We come to the striking contradictions when we try to draw conclusions from all this. When we put in the distances we have talked about and calculate the intrinsical luminosity; we find that typically the luminosity turns out to be a hundred times the total luminosity of a normal galaxy in the op-



Published speed record—and distance and age record—for a galaxy. Now more than decade old, this photograph of radio galaxy in distant cluster of galaxies in constellation Bootes shows form of galaxy with highest known redshift. Figure 2



Theoretical values of spinar properties with time, measured in terms of an overall lifetime, τ. The various curves show what happens to the radius R, the angular momentum J, the luminosity L, and the angular frequency Ω, all of them relative to their initial values. Note how steeply the object grows in luminosity as its end approaches! Something must limit this emission. Figure 3

tical region. This implies a total energy output over a plausible life of 10^6 years of $10^8 M_{\odot} C^2$. Even the brightest quasars probably do not release more than this amount of energy, though they press the limit fairly hard.

So we are led to a picture of the physical nature of the quasar as a ball of some sort with dimensions of a tenth of a light year and a mass of at least 10^8 solar masses. A sounder estimate of mass is to take that lower limit, but divide it by η, the efficiency for generating nonthermal emissions. The value of η depends on the processes generating the energy. If you think it's being generated by nuclear processes as in stars, then η is already less than 10^{-2}, because we can only get 1% of the rest mass out even if we turn all the hydrogen into iron.

If you try to think of an accelerator mechanism that could produce the nonthermal high-energy particle emissions we see, but that would be similar to our earth-based accelerators, you do even worse. The fuel efficiencies of these systems are under 10^{-4}–10^{-6} even neglecting their magnet mass!

If we put in a number like 10^{-6} for η the mass in that tenth-of-a-light-year volume goes up to 10^{14} solar masses! By comparison the central hub of our galaxy might contain 10^9 solar masses in a dimension of some hundreds of light years. We are thus talking of packing 100 000 times that mass into a tenth of a light year, which means either we are dealing with an absolutely singular object, or that our whole picture is somehow wrong.

This I think is the mystery of the quasars. How can you possibly impute to a little region like the solar system a huge mass like a galaxy?

This is not an issue of density. This mass is still far from anything like neutron-star density. It calculates out to be more like the density of rain water than it is of nuclear matter. No abnormal form of matter is implied. What is implied is a total aggregation of mass much greater than we've ever seen in so small a volume. That's the basic contradiction.

I myself don't think that contradiction is so strong. If it turned out this way, I'd be willing to believe it. I think people overwhelmed by the enormity of this problem are not really quite right. Physics does not prohibit aggregates of mass like this. The difficulty has only to do with the plausibility of such aggregates. However, many people were impressed by the difficulty of making long-lasting stable models for such systems, and by the uniqueness of such concentrations of mass, and they said, "Perhaps there must be some other way out."

Rival theories

The first one is Fred Hoyle's suggestion that there is no conservation of energy, then we have no idea what the mass is, or many of the other properties.

Halton Arp, Geoffrey Burbidge and their friends argue that the red shift may not give the distance. Of course as soon as you say there's no distance measure in the red shift, all these contradictions fall by the board.

Arp and company have made a great deal of the association in the sky of certain few quasars with nearby galaxies to persuade us that they are not really distant. There's no question that the associations are curious. But the associations do not persist statistically for the whole quasar population. It's very unlikely, *a priori*, that we should find that four or five of the bright quasars are so near bright galaxies. The suggestion is that these quasars were flung out of those galaxies in some way and if this is so then the red shift has nothing to do with distance. I don't believe that. I believe the following to be true. Sticking to what we believe, most quasars have red shifts. The three or four associated with galaxies also have red shifts. But we'd expect if they were thrown out kinematically, some would be blue shifted and some would be red-shifted. The bulk of quasars are cosmogically red-shifted and very large objects.

I could imagine finding three or four red-shifted ones and zero or one blue-shifted one—but I can't image finding 250 red-shifted ones and no blue-shifted quasar.

Even if Arp does prove that quasars are really associated with the galaxies, I would argue that he is seeing only "dwarf" quasars, secondary to nearby galaxies, flung out with high relativistic velocities, so they do show a proper red shift. They're going away from us at high velocities—nothing to do with cosmology, just with special relativity. And the fact that there are no blue-shifted ones is simply bad luck.

Actually there are a few objects that look suspiciously like blue-shifted quasars—two are called OJ 187, and BL Lacl which are optical polarized. Continuum sources of small size and rapid variability, associated with radio sources and at high galactic latitude. That's all we know about them. They look like quasars but without the tell-tale emission lines. But even if they were blue-shifted quasars, this is what we would expect; the contrast of the emission lines drops seriously when you blue-shift a normal quasar, for its continuum grows stronger toward the red.

Now, for these particular quasars the blue shifts would clearly not be cosmological, if they exist. But the most likely solution is not to argue that no quasar red shifts are cosmological. Rather it is to say that the bulk of the 250 red shifts are still cosmological, but a few kinematic red and blue shifts may exist, to explain the unusual dwarf quasars.

Of course, some people would complain about introducing a second kind of quasar. But if all quasars are local they have to introduce a second kind of radio source! It's interesting that as radio sources, quasars have a structure (when it can be resolved) indistinguishable from the radio sources around some big elliptical galaxies. If I show you a map of a quasar radio source and a map of a strong radio galaxy, nobody can provide criteria to distinguish between them. We are fairly certain we know the dimension of the galactic radio sources. But if you believe the association picture, then you are required to believe that the indistinguishable quasar radio sources are thousands of times smaller in dimension. Either you have to say there are two kinds of radio sources that differ, but look the same, or there are two kinds of quasars that differ, but look the same. I would prefer saying there are two kinds of quasars, because we know much less about them.

In addition, Arp points to alignments in the sky, objects quite far apart in the sky, not close together like the associated ones, but objects which he claims fall in straight lines.

In one or two cases we see a bridge between a galaxy and an object with high red shift; and he proposes that this bridge is a physical connection. To my eyes, it may be or it may not be. People differ on whether the bridge touches the object. A single example is extremely hard to argue from until you have a lot of information about it. Although I prefer to believe that probably there is nothing in Arp's examples, if there is, then we would have to explain them on the bases of relativistic explosions in galaxies, not a simple matter to accept, yet easier than accepting the whole failure of the structure that we have. We must wait for the facts. Probably these mysteries will fade away with more study.

Orthodox theory

As logical discussion these ideas are good; there is no question that all these things may be possible. But it seems to me they ignore the weakest point of the entire argument; this is where the theory that I'm proposing now comes in. (I should say the theory we propose because three groups are involved: the group in Moscow, the MIT group and the Rome–Frascati group around Franco Pacini and A. Cavaliere.)

We have an orthodox view of the situation. Our theory says all these properties of quasars can be understood without assuming any changes in the natural laws of physics. We ask, "Look, who told you that η had to be such a small number?" Suppose, just for fun, $\eta \rightarrow 1$. I give you some magical way of turning rest mass into high-energy particles, without that terrible loss of all those powers of 10. Then, the mass has to be only 10^8 solar masses and the density only 10^{-8} or 10^{-9} gm/cm^3, a very modest gas density. The whole mass would not be larger than we see in the nuclei of galaxies, and the whole thing would begin to look like an exaggerated version of a galactic nucleus, and strike us as very much more orthodox.

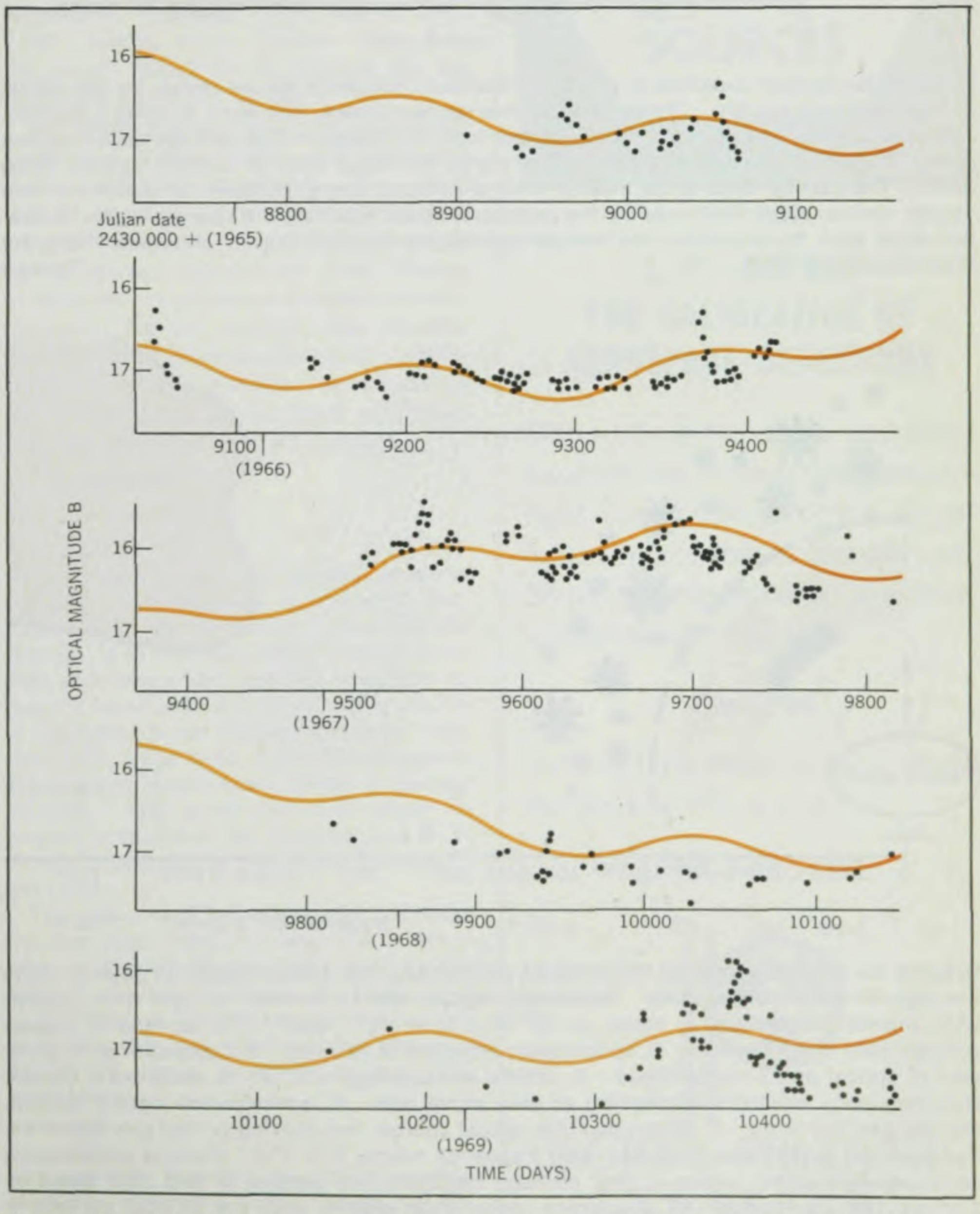
The question is, has anybody ever invented a method for converting rest mass into high-energy particles with high efficiency? Indeed, nobody has ever been able to invent such a thing. (Annihilation helps, but has other troubles.) Instead, we found a mechanism in the sky. Of course I am talking about pulsars, sources like the one in the Crab Nebula that pulses every 30 milliseconds, with beautiful regularity, changing one part in a thousand per year. The point for us is that the pulsar inside the Crab Nebula converts kinetic energy of rotation with efficiency of 10%: (It could be 100% efficiency—the numbers are not that good.) But let's say it is plausible that the efficiency is 10% for converting rotational energy into the energy of fast electrons, and probably of fast protons, which make cosmic rays, x rays, the optical continuum, the bright wisps and all the other things going on in the Crab Nebula. This is impressive, because for 10 years people have tried hard (I myself have published at least two absurd papers on the subject, looking back on them) to find ways of supplying the non-thermal energy of the Crab Nebula (10^4 solar power) and no one was able to find a plausible way. Nobody was smart enough to think of that spinning generator in the middle of the Crab Nebula, the pulsar (except perhaps Franco Pacini).

In essence the pulsar is a unipolar generator. We don't exactly know how it works. We are not in a position to say that we know pulsar electrodynamics. All the theories fit dimensional analysis, but they disagree quite strongly on the physical nature of what's going on, or whether there is a vacuum or a plasma, whether it is essential that pairs are produced, and so on. But the dimensional analysis controls the power as a function of rotation frequency and size to a rough approximation, and although we don't know the mechanism in detail, we have a rough view of what's going on.

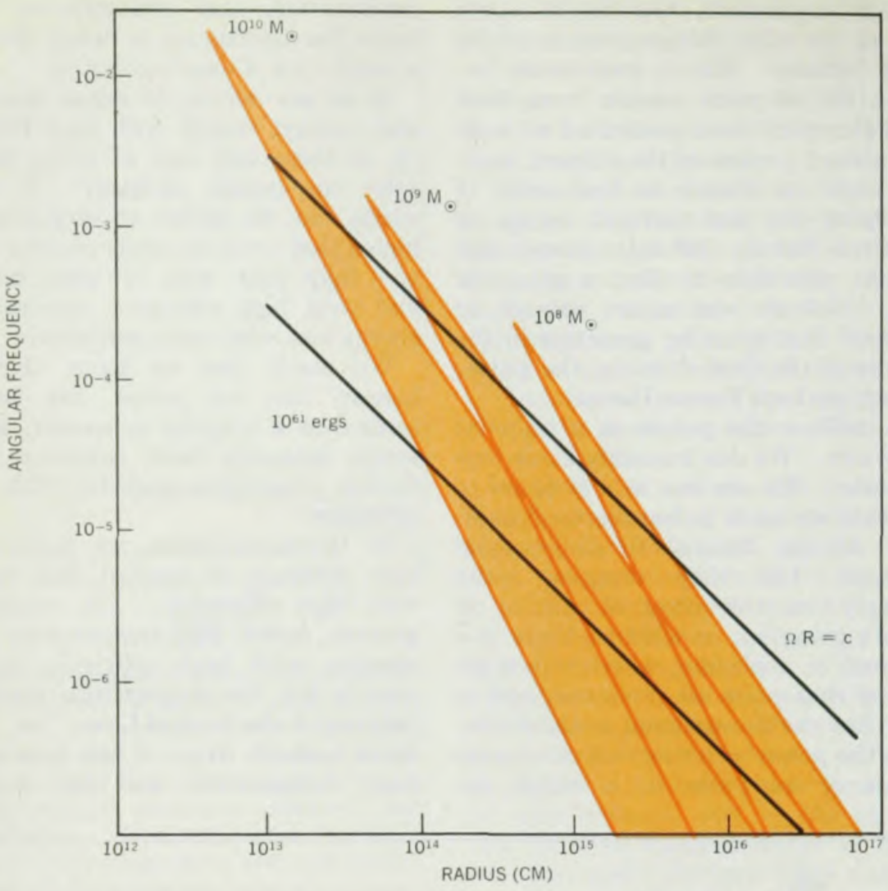
If we are willing to argue that pulsars convert energy with high efficiency, is there any way of using this to solve the quasar problem? In other words, can we invent an object with a high η that could sit easily inside a tenth of a light year, with 10^8 solar masses, and with high efficiency convert that energy into relativistic particles?

We claim that we have, that the quasar, like the pulsar, can be described as a unipolar generator, with a strong magnetic field, coherently producing relativistic particles with high efficiency.

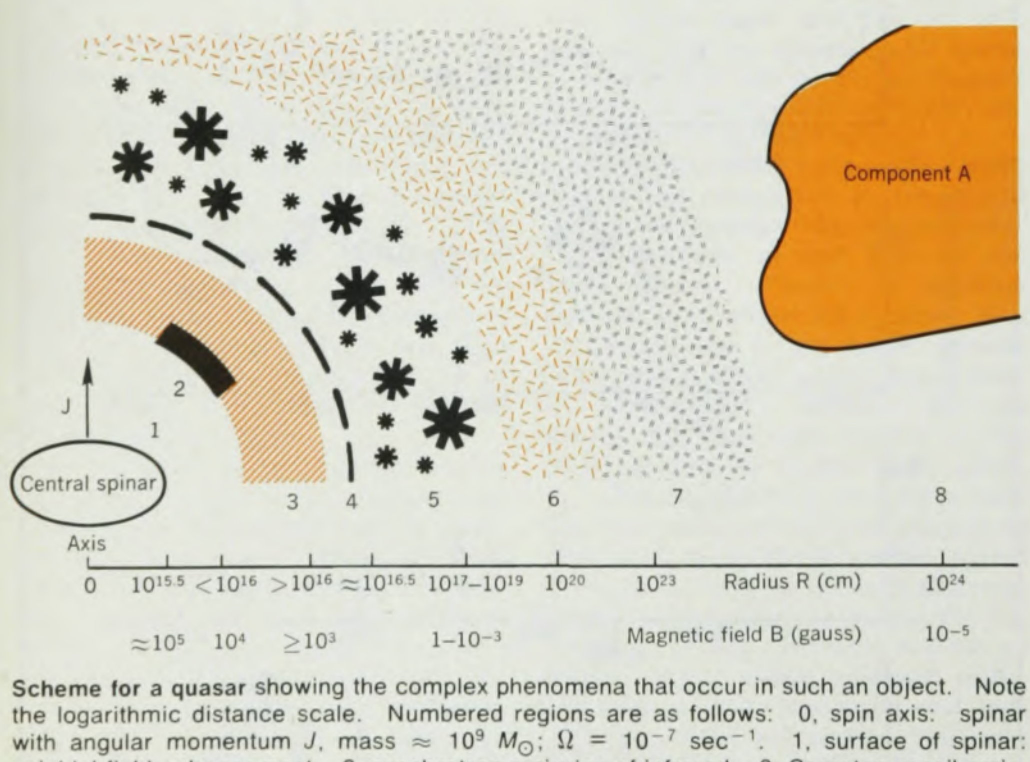
In thermodynamics we know it is very difficult to convert free energy with high efficiency. You cannot in general make high-temperature phenomena with high efficiency out of even a big low-temperature reservoir, because of the Second Law. Yet, I can make a shock tube. I can take air at room temperature and put a little



Periodical variation in optical magnitude of the variable quasar 3C345 observed over several years. These data supplied by T. D. Kinman of KPNO. Figure 4



Domains for quasar evolution in plane of rotational frequency versus radius for the model of cold coherent spinars. Three different masses are shown, with each defining a triangle. The lower speed limit of each triangle comes from the theory of high-entropy supermassive stars (Wagoner); the upper defining line marks the rough limit of stability against flying apart. The parallel lines show a lower limit of minimal energy suitable for quasars in late stages, and an upper limit fixed by the peripheral speed reaching the speed of light. Evolution must work its way within the triangle appropriate for each mass. Naturally, these are idealized relationships. Figure 5



Scheme for a quasar showing the complex phenomena that occur in such an object. Note the logarithmic distance scale. Numbered regions are as follows: 0, spin axis: spinar with angular momentum J, mass $\approx 10^9\, M_\odot$; $\Omega = 10^{-7}\ \mathrm{sec}^{-1}$. 1, surface of spinar: poloidal field enhancement. 2, synchrotron emission of infrared. 3, Compton-recoil emission of optical and x-ray continua. 4, critical surface $R_{\mathrm{CR}} \approx c/\Omega$. 5, radio-burst clouds, radiofrequency emission (expanding as they move out). 6, emission-line optical source, excited gas filaments. 7, absorption-line optical source, fast-moving cooled gas filaments. 8, weak-field synchrotron plasma, radio frequency mainly $\lambda > 1$ m. Particle acceleration continues throughout region 2, and perhaps beyond. The general B field falls about as $1/r^2$ or $1/r^3$ (or steeper for multipoles higher than dipole) until the ciritical surface is reached; outside that, it is mainly toroidal, and falls as $1/r$. The whole volume is traversed by a large output of relativistic protons. Figure 6

pressure energy into it and puncture the shock diaphragm, and watch the shock converge and make a spark at the end. It's a remarkable demonstration. But what is the price for that? The price is that while I can make in a small amount of matter a temperature of a million degrees, from a 300 K source, I am able to do that only because I throw away 99.9% of the energy, or even more. I have low-efficiency conversion. A small amount of energy can be emitted in a very high-temperature form.

But if it's the other way around, if some degrees of freedom have a high temperature to begin with, it's easy for them to pass their energy on with high efficiency to degrees of lower temperature.

What is the characteristic energy per degree of freedom? For a very high-energy cosmic-ray particle a typical number would be 10^{16} volts per particle. That's an enormous energy; it would correspond to around 10^{20} K. But if I had a gas at 10^{21} K, I can easily convert 90% of its energy into fast particles with these energies. That is exactly what the pulsar does. A pulsar is an object in which a very large amount of energy has gone into one degree of freedom—rotation. (If you object that it's not a perfectly rigid rotator, we could agree that perhaps it's a handful of degrees of freedom.) The point is, the energy is practically coherent.

The characteristic temperature of a pulsar, then, is some 10^{50} ergs in the one rotational degree of freedom; that's equivalent to 10^{64} or 10^{65} K! Obviously it's no trouble at all for the pulsar to make cosmic-ray particles at a mere 10^{20} K. It can hardly degrade itself any other way, because it is much too large a jump to drop to normal temperatures; it has to seek intermediate steps all the way down.

On thermodynamic grounds, to gain high efficiency for making relativistic particles, you must store a lot of energy in a single degree of freedom.

Can we imagine a pulsar-like mechanism operating in quasars, namely a coherent magnetic field attached to a rotating object that has all the energy you like? Try to envision that a quasar has a central spinar, an object with a mass of 10^8 solar masses, typically, and a dimension well under one-tenth of a light year. It has a modest magnetic field of 10^5 or 10^6 gauss, nothing very remarkable. But it has a peripheral speed that has to be very high—0.01 to 0.1 of the velocity of light.

It would then have a period of rotation, not of 30 milliseconds like the tiny pulsar, but of once per year, or once every five years.

Such an object can indeed accelerate particles by the pulsar mechanism to fling out relativistic particles. It can convert its kinetic energy of rotation into cosmic rays with an efficiency of the order of one-half. Just as with the pulsar, the kinetic energy of rotation is originally supplied by gravitational energy. Now, as the pulsar loses energy, it slows down. But that's only because it is a rigid condensed structure, which is no longer able to contract. The spinar is made of ordinary gas with a density of some 10^{-8} grams per cc and a temperature of maybe 10^5 K—just enough to keep it well ionized. When this object loses rotational energy it by no means slows down. It simply continues to contract and, like the familiar figure skater who pulls in her arms, it spins faster and faster as it contracts; the faster it spins, the higher its luminosity becomes, the greater its production of fast particles and visible light.

The classical theory tells us that whenever you take an erg out of the kinetic energy, the gravitational energy can supply up to two ergs, one of which supplies the loss, while the other goes to increase the kinetic energy.

We have made crude studies of the evolution of what happens to a coherent rotating body with a magnetic field, which starts out very large and very slow with a very weak field, and gradually spins up, faster and faster so that it becomes more and more luminous. The luminosity increases more and more rapidly until it becomes infinitely bright with time. This singular end-point is obviously an idealization; something else must end the process before $t \to \tau$ (figure 3).

We can point to hints from observation that quasars are in fact related to pulsars. Figure 4 shows that quasar 3C 345 produced three successive mighty pulses, like a pulsar, but one year apart, or 321 days to be more exact. (Each pulse has a luminosity of 10^{12} or more times that of the sun.) With quasars we would not expect such patterns to continue indefinitely; the quasar will behave more like the sun than a rigid pulsar. If you look at the sun from a great distance, you'll see the rotation of 27 days. No sun spot lasts more than a few recurrence patterns, a few times 27 days. Spots appear and disappear in different positions. But if you measure spottiness, you'd see this shifting 27-day pattern, and I think that's what we see for 3C 345 every 321 days.

These data are striking but obviously don't prove anything. It would take a few more pulses before people will be convinced by 3C 345.

Figure 5 gives an idea of the domain in which quasar spinars would exist. Various upper and lower bounds for the total energy are shown in the radius and circular-frequency plane. The objects somehow evolve within the region of the plane shown, spinning faster as they shrink in size.

They begin in the centers of remote galaxies; anywhere save the center, tidal forces would disrupt them. In the center, when circumstances of magnetic field and spin direction are favorable, they slowly contract from conditions not very unlike the central interstellar regions of a normal galaxy. Since they live only a few billion years, they mostly have exploded in the distant past, and are seen only when we look back, far back into that past, out to large Z.

For Z larger than 3 or so, not even the primeval galaxies had formed, so that we find no quasars.

Their end is uncertain. They might—but I doubt it—shrink to such small sizes and high spin speed that they become spinning black holes. They might simply shed their fringing fields at high luminosities—the plasma is then very highly stressed—and now, no longer very magnetic externally, or very luminous, live a thousand times longer as sleeping tops, so to say. They might even fission into two daughters, which fly to become the big radio lobes we often do see.

All these matters must be examined; perhaps a better theory will show one step or another impossible. But until that is done, I prefer to think of this general scheme, a scheme due to a number of groups world-wide from Boston to Moscow, as at least a promise of completeness for our present-day physics, the physics of Newton, Maxwell, Alfvén, Bohr, Einstein, Hubble, to which no grand exception has yet been exhibited, even by the extraordinary quasars.

References

There is surprisingly little general review of quasars. The best book is that of G. Burbidge and E. Burbidge, *Quasi-Stellar Sources*, W H Freeman, 1967. A more up-to-date and manysided but less complete account is found in D. O'Connell, editor, *Nuclei of Galaxies*, North Holand-American Elsevier, 1971. The work of the Moscow group appears over several years, mostly in Russian journals. One good technical paper in English is that of L. M. Ozernoie and B. V. Somov in Astronomy and Space Science **11**, 224 (1971).

The pulses of 3C345, which may yet make the case clear, were first described in Astrophysical Journal **152**, 357 (1968), by T. D. Kinman, E. Lamla, T. Ciurla, E. Harlan and C. A. Wirtanen. The remarkable observations of H. Arp are well-described by him in a number of places, especially Science, **174**, 1189 (1971).

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This article is based on the transcript of an informal, illustrated talk presented to an undergraduate seminar at Harvard University. □