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QUASISTELLAR OBJECTS AND SEYFERT GALAXIES

Are these two classes of distant objects related? Evolution of dense stellar clusters, so crowded with stars that collisions occur, yielding more massive stars and supernovae, could be the common origin of them both.

STIRLING A. COLGATE

CONCEPTS of the size and geometry of our observable universe depend largely on what we make of the mysterious, distant quasistellar objects. Seyfert galaxies, which have a bright nucleus at the center of an otherwise normal galaxy, have been another source of mystery. Observations of their optical and radio emissions show fluctuations. If we can find a relation between quasistellar objects and Seyfert galaxies, suggesting a similar origin and an evolutionary link, we may be able to use the fluctuating emission as a new yardstick for the universe.

We can arrive at a relation with an evolutionary theory that postulates collisions within ultradense clusters of stars leading to formation of very massive stars and supernovae, with neutron stars remaining as the supernova residue. The densest star clusters, on this theory, then reproduce the observed properties of quasistellar objects, and star clusters with densities less than the maximum yield the properties we observe in Seyfert galaxies.

Astronomical scale

When Copernicus finally proved that the earth does revolve around the sun, man's search into space began. Since then, human intellect has interpreted the results of observations further and further out into the universe. By triangulation first the earth's diameter, and then the earth–sun distance, could be determined. The mass of the earth and Kepler's laws confirmed the concept and understanding of the earth's orbit around the sun. Parallax, or the change in apparent direction to distant stars as the earth orbits the sun, enabled the distance to nearby stars to be measured in the new unit "parsec," the distance for which the parallax is one second of arc. One parsec is 3.1×10^{18} cm = 3.25 light years. Other stars could then be compared with the sun and the prevalence of stars with the solar mass ($M_{\odot}$) observed. Binary stars and star clusters established the range and also theories of stellar structure.

A particular class of stars, the Cepheid variables (which vary in luminosity with periods of hours or days) became an easily recognized standard of luminosity—and therefore distance—and, as a consequence, the way was open to recognize a hierarchy of stellar systems more distant than our own "Milky Way." First the Magellanic Clouds (of stars), observable only in the southern hemisphere, and then the great nebula in Andromeda fairly demanded the concept of "other galaxies." The child-like name "Milky Way" for our own wondrous association of stars (10^{11} of them) suddenly became even more parochial when we recognized the semi-infinite population of galaxies in our universe. Just as the statistically homogeneous set of objects called stars—and the subset of

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SYMBOL DEFINITIONS

c—velocity of light
G—gravitational constant
k—Boltzmann's constant
$M_\odot$—solar mass
m—stellar mass
N_c—number of stars in central cusp of star cluster
N_s—number of scattering events
R_c—radius of cusp in star cluster
r_s—stellar radius
T—temperature
V_s—stellar velocity
V—relative velocity of two stars before collision
W_B—average binding energy of the matter in two colliding stars
z—red-shift coefficient
ρ_r—thickness of average star
ρ_g—gas density in galaxies
σ—scattering cross section for star clusters
σ_c—coalescence cross section for stellar collisions
σ_e—cross section for cusp evolution
σ_r—cross section for relaxation
τ_r—relaxation time
ω_p—plasma frequency

Cepheid variables—became the unit to measure so-called "nearby" distances, so galaxy types became a yardstick in the nearby universe.

A new pattern was then observed; galaxies recede from us with a velocity that is greater the farther away they are. A Doppler shift toward the red of the standard composite stellar spectrum established the recession. This "red shift" of spectral lines, discovered by Edwin Hubble, became the new yardstick of the universe. Because the red shift was superimposed on an already known stellar spectrum, its interpretation as a recession velocity (expanding universe) became almost certain. We could recognize galaxies with redshifts of 0.2 (receding from us at a velocity of two tenths of the speed of light); the spatial distribution confirmed a "nearby" uniformly expanding universe. Is it truly expanding uniformly to infinity? Or is there a relativistic curvature? The insatiable curiosity of man—as Rudyard Kipling would say: "Oh! best beloved"—demands, even agonizes for, an answer. Just as nature abhors a vacuum mankind goes "ape" with an unanswered question. To extend observation further we wanted a new and brighter class of objects than galaxies.

Quasistellar objects

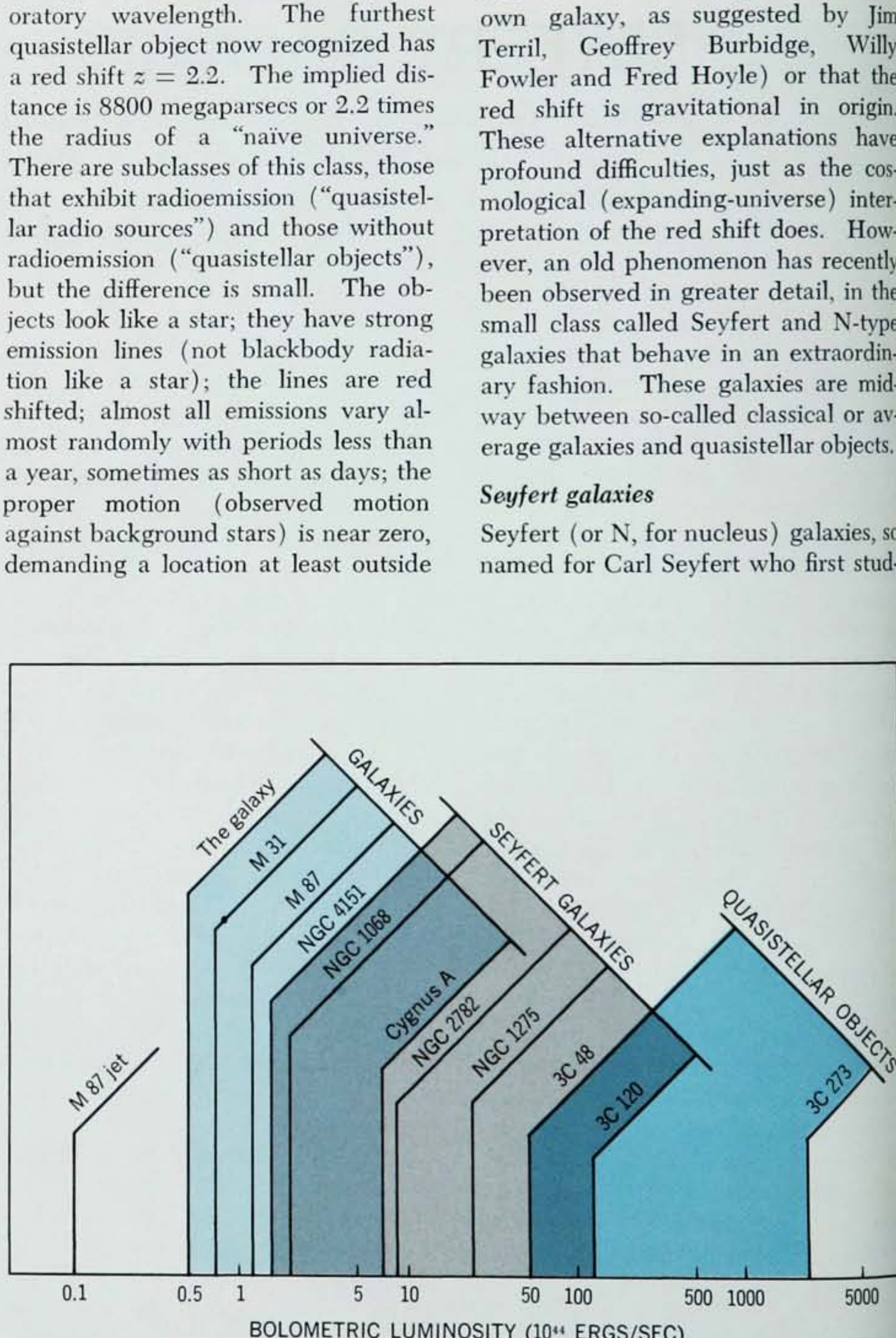
As if to answer this need Maarten Schmidt discovered quasistellar objects —but what a class they made! Constancy had been the almost universal rule for astrophysical phenomena, man's life being such a blink in the eon of time; now the most distant objects, the ones with the biggest red shift, were blinking away like a signal ship. Could they really be as far away as their red shift implied?

Red shift is measured as z, the change in wavelength divided by laboratory wavelength. The furthest quasistellar object now recognized has a red shift $z = 2.2$. The implied distance is 8800 megaparsecs or 2.2 times the radius of a "naïve universe." There are subclasses of this class, those that exhibit radioemission ("quasistellar radio sources") and those without radioemission ("quasistellar objects"), but the difference is small. The objects look like a star; they have strong emission lines (not blackbody radiation like a star); the lines are red shifted; almost all emissions vary almost randomly with periods less than a year, sometimes as short as days; the proper motion (observed motion against background stars) is near zero, demanding a location at least outside our galaxy. There the simple things end.

If the time of the variability is indeed as short as a day, the dimension must be no larger than a light day (3×10^{15} cm; for comparison the solar radius $= 7 \times 10^{10}$ cm). Yet how could we pack an object inside this dimension when the energy output (10^{47} ergs/sec, largest in the infrared) corresponds to a rest mass of 1.5×10^6 suns in a million years! Several alternatives exist; they are that the distance is not as great as the Hubble distance—red-shift relation indicates, that the red shift is due to a local phenomenon (relativistic ejection of condensed objects from our own galaxy, as suggested by Jim Terril, Geoffrey Burbidge, Willy Fowler and Fred Hoyle) or that the red shift is gravitational in origin. These alternative explanations have profound difficulties, just as the cosmological (expanding-universe) interpretation of the red shift does. However, an old phenomenon has recently been observed in greater detail, in the small class called Seyfert and N-type galaxies that behave in an extraordinary fashion. These galaxies are midway between so-called classical or average galaxies and quasistellar objects.

Seyfert galaxies

Seyfert (or N, for nucleus) galaxies, so named for Carl Seyfert who first stud-



BOLOMETRIC LUMINOSITIES for galaxies, Seyfert galaxies and quasistellar objects. The Seyfert-galaxy measurements are from F.J. Low and D.E. Kleinmann, proceedings of the conference on Seyfert galaxies, Arizona, 1968. —FIG. 1

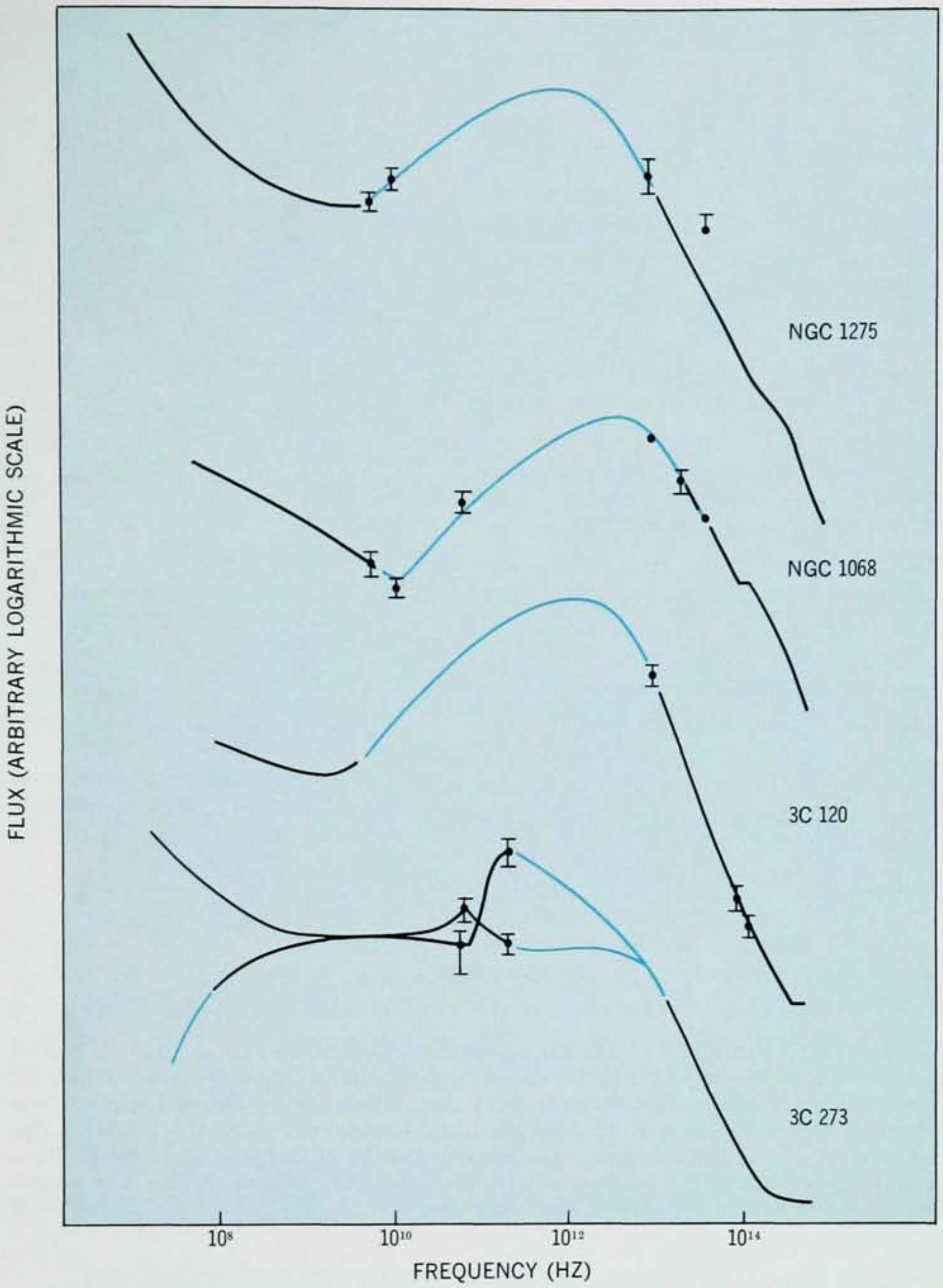
ied them, comprise about 1% of all galaxies, and differ from other galaxies only in having a small central region, far brighter than the center of the average galaxy, whose optical emission is again strong in emission lines—implying large regions of low-density hot gas. Moreover, the optical and radio emissions have recently been observed to fluctuate, as if outbursts occurred; also, as with quasistellar objects, the largest fraction of the energy is emitted in the infrared. Thus the observational behavior of the center of Seyfert galaxies is strikingly similar to that ascribed to quasistellar objects.

Geoffrey Burbidge, Margret Burbidge, and Allan Sandage[1] first drew attention to this extraordinary galaxy phenomenon, and indeed there is every reason to postulate that the cores of Seyfert galaxies are part of a continuous sequence of objects that culminate in quasistellar objects. If a theory[2-6] of this sequence of objects should prove successful, there is the exciting possibility that the intrinsic luminosity at some stage of their recurrent outbursts can be "identified" and predicted. As a consequence these most luminous objects can become reliable measuring sticks for determining the bounds—if any—of our universe.

A possible relation?

Seyfert galaxies appear as normal galaxies in the region outside their core, and they obey the normal galaxy size–distance and red-shift–distance relations. At still greater distances, corresponding to the red shift of quasistellar sources, we would not see the normal galactic structure. With the assumption that the quasistellar objects are at a distance corresponding to their red shift, the continuous observational morphology of these galaxies and quasistellar objects includes the phenomena of luminosity in the optical, infrared, and radio frequencies, relatively rapid fluctuations, line emissions, broad spectral classification and size.

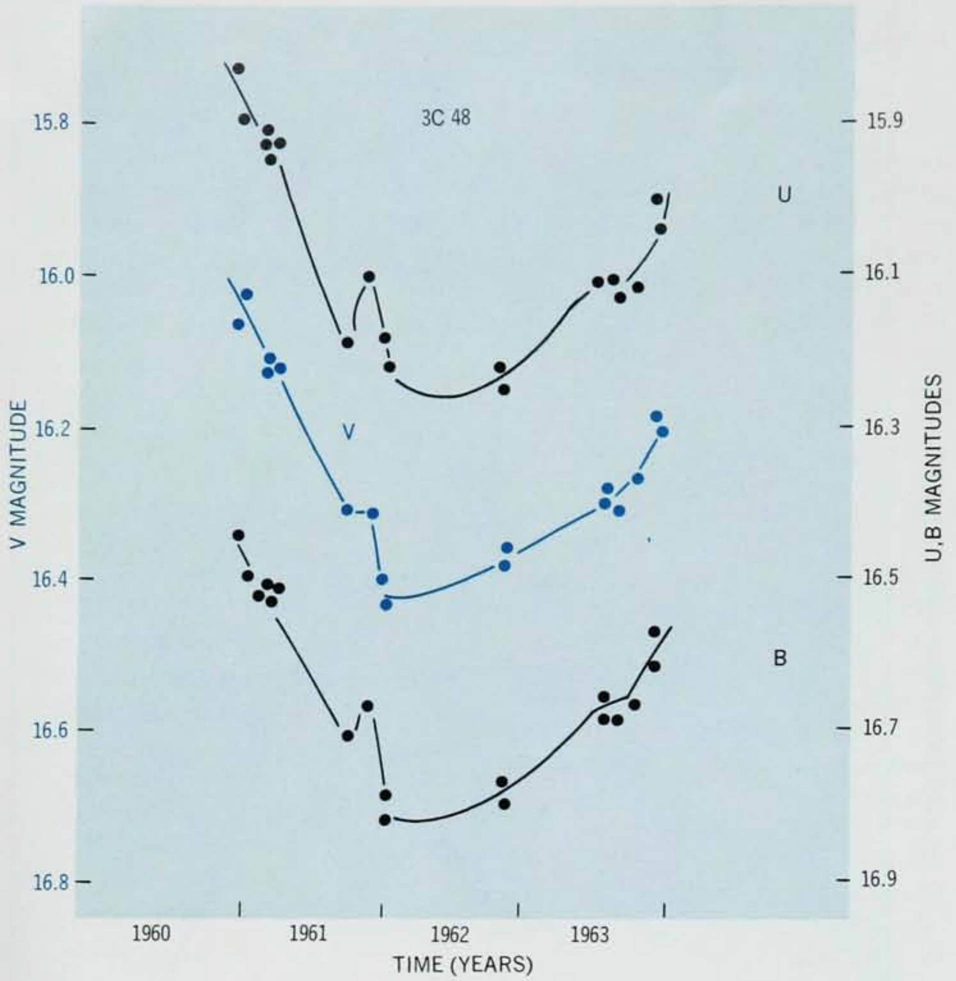
The theory I present here depends on the evolution of an ultradense cluster of stars—so dense, in fact, that collisions occur and lead to massive stars and supernovae. The proposed source of the energy released is the supernova residue, a neutron star bound gravitationally at a lower negative energy than any other form of matter. Like many astronomical theories the probability of it being correct is of the order ϵ (arbitrarily small), but the "insatiable curiosity . . . Oh! best beloved" is sufficient motivation to propose and then propose again.



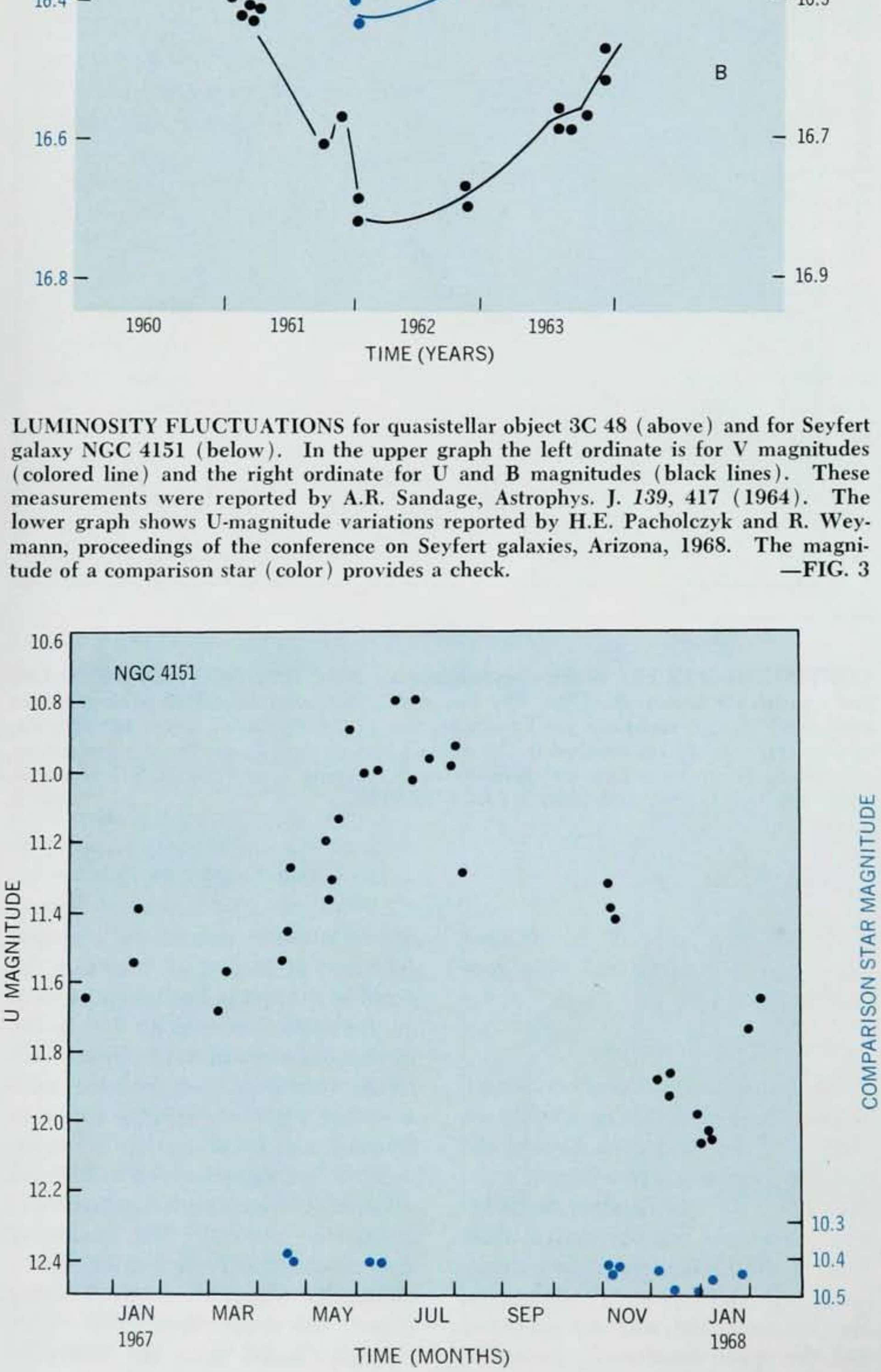
CONTINUUM SPECTRA of three Seyfert galaxies, NGC 1275, NGC 1068 and 3C 120, and quasistellar source 3C 273. The flux scale (ordinate) is shifted arbitrarily for each case. Large variations are known to exist in the frequency range 10^9–10^{11} Hz, so no weight should be attached to the colored part of each line. The Seyfert galaxy measurements are from Low and Kleinmann, as in figure 1, and the 3C 273 measurements are by F.J. Low, Astrophys. J. *142*, 1288 (1965). —FIG. 2

Evidence for similar origin

Table 1 summarizes the observational similarities, including the possible exception of the absorption lines of the quasistellar objects clustering at a red shift $z = 1.95$. As Geoffrey Burbidge would comment, this observation alone reduces the probability of any theory being correct to order ϵ^2. However, Maarten Schmidt[7] recently proposed that the space density of quasistellar objects is highly nonuniform and concentrated at large $z \approx 1$ so that the possible absorption-line exception may be due more to cosmology than to the mechanism of quasistellar objects. Instead, we will comfort ourselves with assuming a probability ϵ by noting in figures 1 and 2 the overlap in magnitude of luminosity as well as spectral similarity between Seyfert galaxies and quasistellar objects. The luminosity fluctuations of a Seyfert galaxy and a quasistellar object are shown in figure 3; note the similar time scale. Thus fortified, "based upon the turn of a



LUMINOSITY FLUCTUATIONS for quasistellar object 3C 48 (above) and for Seyfert galaxy NGC 4151 (below). In the upper graph the left ordinate is for V magnitudes (colored line) and the right ordinate for U and B magnitudes (black lines). These measurements were reported by A.R. Sandage, Astrophys. J. *139*, 417 (1964). The lower graph shows U-magnitude variations reported by H.E. Pacholczyk and R. Weymann, proceedings of the conference on Seyfert galaxies, Arizona, 1968. The magnitude of a comparison star (color) provides a check. —FIG. 3

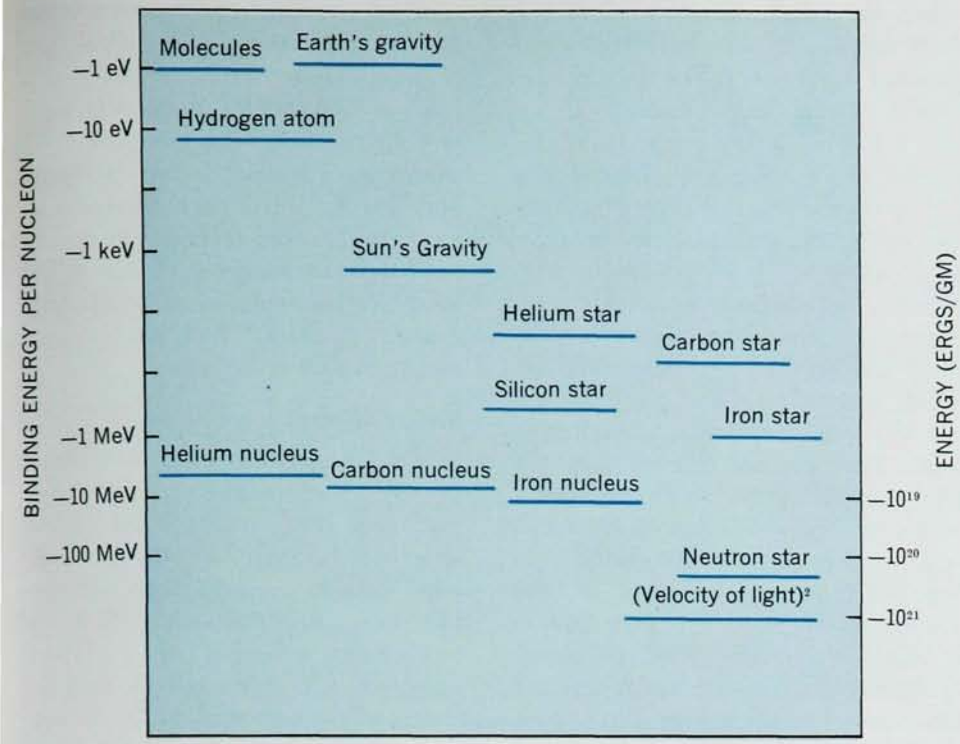


plausible phrase and thickening the erudite verbal haze,"[8] we turn to theory.

Theory and energy

In the construction of a theory of such violent events, the overwhelming limitation we must consider is energy and the rate at which it is released. If energy is emitted from a given region in space either the net negative binding energy of the residual rest mass must be increased or antimatter must be annihilated. The postulate of antimatter merely removes the problem of binding energy to a prior space and time so that, assuming normal matter, the problem of cosmic violent events is one of finding the mechanisms for a sudden increase in binding energy of matter.

We are well aware of the binding energies of various states of matter; figure 4 outlines a few of the more usual ones as well as the less well recognized gravitation binding. Three scales of units are given to better associate the physics with each phenomenon; electron volts for molecular phenomena (10^{12} ergs/gm molecular weight), MeV for nuclear phenomena (10^{18} ergs/gm molecular weight) and c^2 (9×10^{20} ergs/gm) for gravitational phenomena. Clearly, molecular binding and the earth's gravitational binding are nearly the same; hence chemical rockets work. We note also that the nuclear binding energy of helium and heavier elements is large (4×10^3 times the gravitational binding of the sun); hence, fortunately, a main-sequence star (the sun) burning hydrogen to helium has a lifetime longer by this same factor than its radiative diffusion time constant (Helmholtz contraction time). Finally the strongest binding of matter is postulated (and one must remember that this *is* a postulate) to be the neutron star. The postulate depends on nuclear-interaction potentials as well as on general relativity, but as neither theory is used for conditions far beyond experiment (nuclear-scattering experiments and the gravitational bending of light) the detailed calculations of Sachito Tsuruta and A. G. W. Cameron[9] are probably correct in indicating an upper limit to the binding energy of matter equal to $0.2\ c^2$/gm, or 200 MeV/nucleon for a proper mass of no more than $2\ M_\odot$. This is 50 times nuclear binding and is the logical source of energy for violent cosmic events. Note in table 1 the minimal



NEGATIVE BINDING ENERGY in various states shown on a logarithmic scale relative to the free proton and electron. The state of matter with the lowest binding energy is thought to be that of the neutron star. —FIG. 4

energy requirement for quasistellar objects of 1.5×10^6 solar rest masses ($M_\odot c^2$).

Sudden release of energy

The possible nuclear binding energy that is available for a violent event is further restricted by the requirements of relatively small size and sudden release. The burning of hydrogen to helium is severely restricted because of the requirement for emission of two neutrinos to complete the reaction; the reaction He + He $\rightarrow$ Be^8 is endothermic and the reaction 3He $\rightarrow$ C^{12} is too slow. As a consequence, explosive events depending on nuclear binding energy alone are restricted to carbon and oxygen.

The nuclear energy available from carbon burning to completion (iron) is then small, about 0.5 MeV/nucleon. Yet the mean ejection velocity of the most recently observed supernova remnant,[10] (Tycho's nebula) for which the deceleration correction is smallest, places a lower limit of 2–3 MeV/nucleon for the ejected matter. When one further considers that for any supernova model yet proposed an equal or greater amount of work must be performed by the ejected matter against the gravitational attraction, the total observed ejection energy of 2–3 MeV/nucleon is well beyond that likely to be derived from nuclear binding alone.

Table 1. Observational Similarities

Observation	*Seyfert and N-type galaxies*	*Quasistellar objects*
Infrared luminosity	10^{45}–10^{46} ergs/sec	10^{46}–10^{47} ergs/sec
Optical luminosity	10^{44}–10^{45} ergs/sec	10^{45}–10^{46} ergs/sec
Radio spectrum, wavelength less than one meter	flat	flat
Radio spectrum, wavelength greater than one meter	synchrotron power law	synchrotron power law
Infrared fluctuations	?	possible
Optical continuum fluctuations	0.5 magnitude/year	10 magnitudes/year
Optical line fluctuations	none	none
Radio fluctuations, wavelengths less than one meter	0.5 magnitude/year	10 magnitudes/year
Radio fluctuations, wavelengths greater than one meter	none	none
Optical polarization	small	small
Radio polarization	large	large
Radius	30–50 parsec	less than 15 parsec
Absorption lines	?	strong
Absorption-line red shift		half and half

Supernova theory

On the other hand, models of supernovae that depend on the release of the binding-energy difference between the initial state of a highly evolved star and a final neutron-star remnant core have been successful in demonstrating a supernova mechanism generally consistent with observation. Figure 5 shows a numerical calculation of the dynamical collapse of a 10 $M_\odot$ star initially made unstable by the mechanism of endothermic decomposition of iron, first proposed by Geoffrey Burbidge, Margret Burbidge, Fowler and Hoyle.[11] The binding energy of the neutron star appears first as heat ($kT \approx 50$ MeV) and is thermally conducted by a neutrino flux (in thermodynamic equilibrium) to the external matter, which is in turn blown off by the thermal pressure. This blown-off material gives rise to the observed phenomena. Some of the material has a velocity just sufficient to escape the gravitational potential well, and it "oozes" out into space; some of it (the mass average observed for Tycho's nebula) has substantial velocity (2–3 MeV/nucleon); and a relativistic fraction, 10^{-4}, has an energy distribution corresponding to the observed spectrum of cosmic rays. How can this violent event be associated with the still more violent events of Seyfert galaxies and quasistellar objects?

It should be emphasized that the usually observed supernova, although it is (when at maximal luminosity) as luminous as a whole galaxy, has nevertheless only 2×10^{-4} of the peak bolometric luminosity of the most luminous quasistellar object (3C 273 in the infrared). On the other hand the kinetic energy released in a supernova event, calculated from the observations of Tycho's nebula and implied by the theory, is about 10^4 times the luminous energy. It appears therefore that, if the kinetic energy of a supernova were converted into radiation in a time of the order of weeks, the luminosity would be equivalent to the maximum observed for a quasistellar object. An initial attempt in this direction[12] indicated that such a conversion could take place in a collision between the ejected matter from a supernova and an ambient gas of density 10^{-17} gm/cc (6×10^6 particles/cc), equivalent to that inferred from the ratios of observed spectral lines. On the other hand no reason was suggested for the required extremely high frequency of supernova events, that is, 5–10 per year.

There is now a valid reason[6] to expect this high frequency of supernova events as the result of the final evolution of an extremely dense cluster of stars. Moreover the maximal supernova rate, lifetime, gas density, fluctuation behavior, and some of the spectral features of quasistellar objects all logically result from the extremum condition of the first assumption; namely, the densest possible cluster of stars. Furthermore a cluster of stars less dense than the extremum gives rise to the phenomena associated with Seyfert galaxies and, in addition, predicts a cluster radius in agreement with the observed radii of these galaxy cores.

Star-cluster evolution

The evolution of a cluster of stars depends on the scattering by gravitational attraction of one star by another when the whole ensemble of stars is held together by their collective gravitational attraction. The relation between force and radius, $F = (m_1 m_2 G)/r^2$, is the same radial behavior as for oppositely charged particles, so that the concept of plasma thermalization with a relaxation time, $\tau_r = [n \langle \sigma v \rangle]^{-1}$, where σ is the scattering cross section, is entirely analogous to star-cluster relaxation. Indeed the original derivation of "dynamic friction" was first made for star clusters by Subrimanian Chandrasekhar. This analysis showed that the time for a relatively small star cluster within the galaxy to evolve, by evaporation of stars from the cluster into the continuum distribution of the galaxy, was 88 τ_r. This long time is associated with the relatively small probability for a single star to achieve the required escape energy, three times the mean thermal energy (as predicted by the virial theorem). The cluster ages resulting from this analysis then agreed with the results of stellar evolution.

On the other hand the internal structure of a cluster of stars can evolve to a different density distribution without requiring evaporation of stars from the cluster. Sebastian von Hoerner[13] has investigated the formation of a central cusp of high-density stars and has recently derived an approximate solution for the formation of the central cusp of stars. His solution shows that a large star cluster bifurcates into separate distributions with the lower total-energy stars tending to form a central high-density cusp that decreases in total number and increases in density until the cusp runs out of stars. The time for this evolution is significantly shorter (15–20 τ_r) than that for evaporative evolution, 88 τ_r.

Stellar disruptive collisions

In the process of evolution to higher density there is a finite probability that two stars may collide. If an imaginary box moving at the center-of-mass velocity contains both stars before and after collision, and if the total energy in the box before collision, $(\Delta V)^2/2 + W_B$, is negative, then the matter of the two stars *on the average* must remain bound. ΔV is the velocity relative to the center of mass a large distance before collision and W is the average binding energy (negative) of the matter in the two stars. For a Maxwellian distribution of velocities, the collision-energy distribution in the center-of-mass system is the same as the thermal-energy distribution in the cluster. Therefore the condition for stellar collisions resulting in disruption of a star of polytropic index 3 is, from Lyman Spitzer and William C. Saslaw[5]

$$\frac{V_s^2}{2} > \frac{3\,Gm}{4r_s}$$

where $V_s^2/2$ is the mean stellar kinetic energy, m is the mass of the star and r its radius.

On the other hand the virial theorem for the central cusp of the star cluster predicts that

$$\frac{V_s^2}{2} = \frac{GN_c m}{4R_c}$$

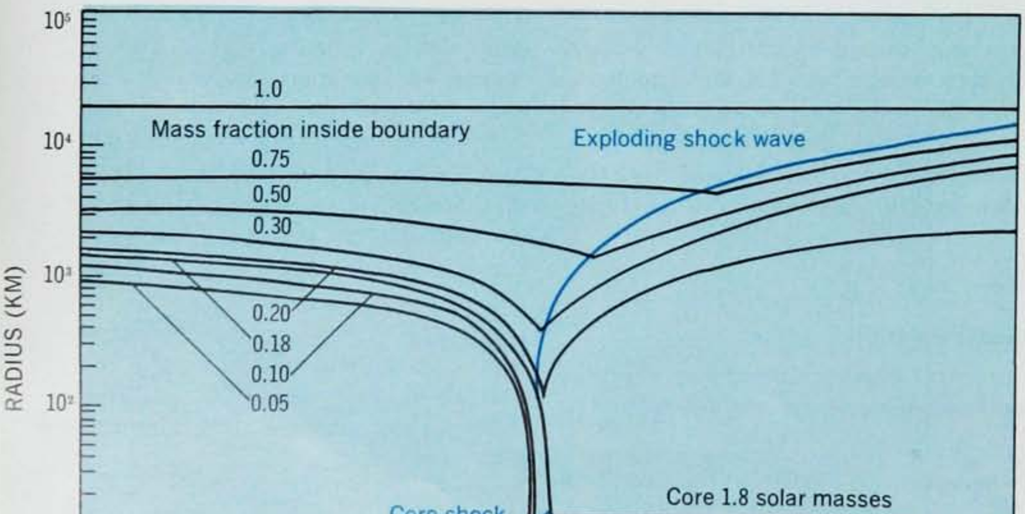
As a consequence disruptive collisions occur when

$$\frac{N_c}{R_c} \geq \frac{3}{r_s}$$

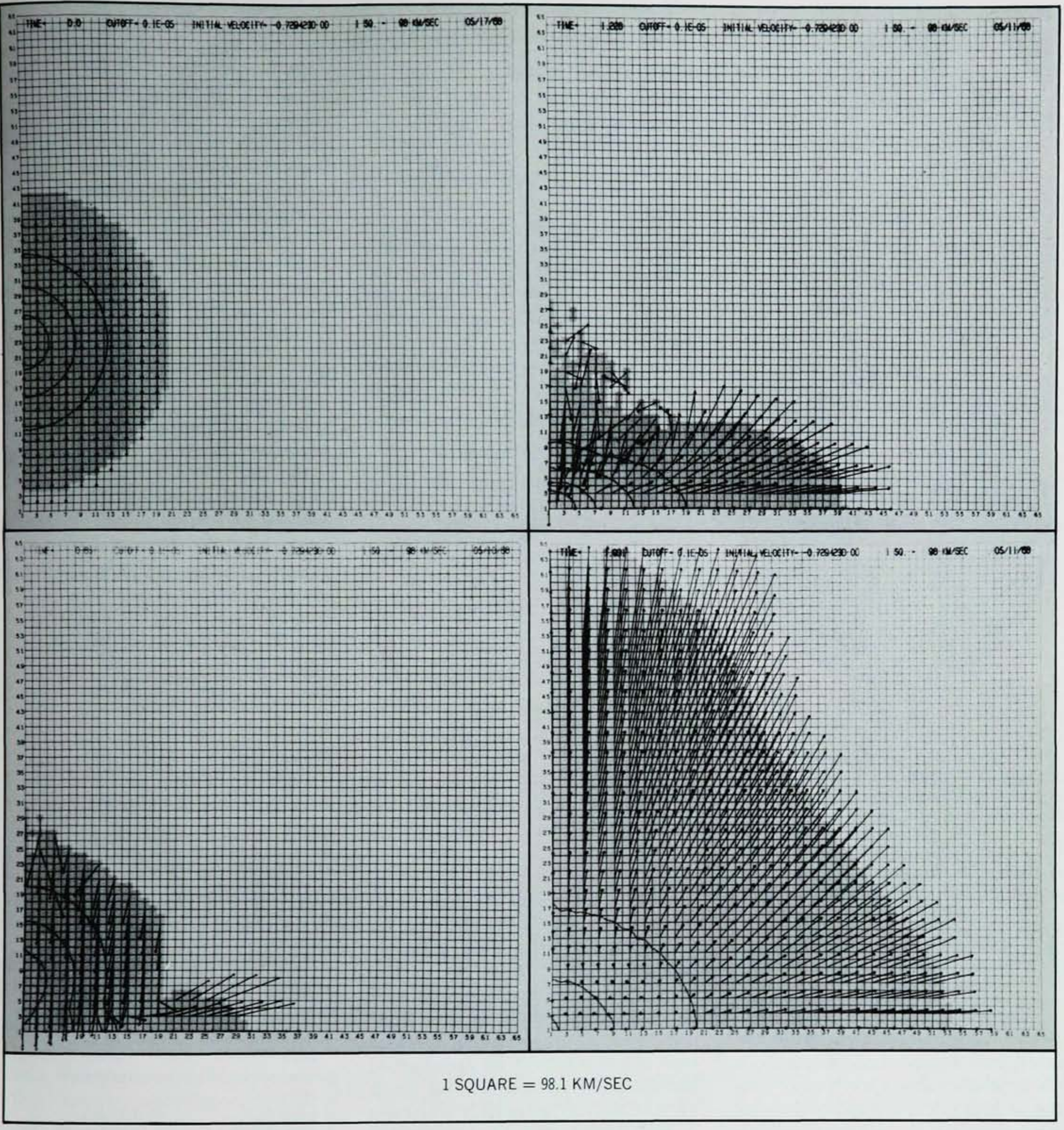
Here N_c is the number of stars in central cusp of radius R_c and r_s is the radius of the average star—initially assumed to be like the sun. Thus disruptive collisions occur at a cluster radius scaled from the star radius by the total number of stars.

Coalescence

When the relative kinetic energy is insufficient for disruption, the two stars



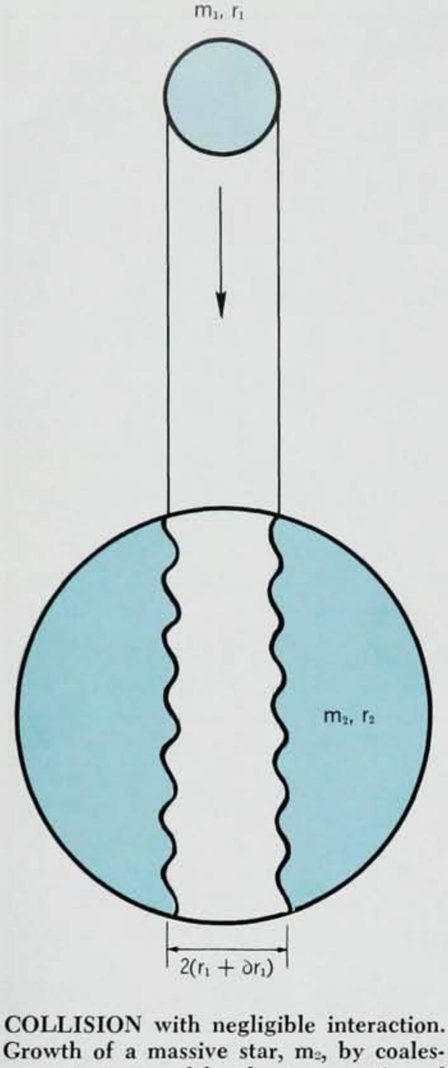
DYNAMICAL COLLAPSE of a supernova with mass ten times that of the sun, shown as the variation of radius with time. During the initial collapse the neutrino energy is assumed to be lost from the star, but at the time of formation of a core shock wave a fraction of the neutrino energy is deposited in the envelope. Deposition ceases when the explosion terminates the imploding shock wave on the core. From S.A. Colgate and R.H. White, Astrophys. J. *143*, 660 (1966). —FIG. 5



HEAD-ON COLLISION of two stars, identical polytropes of index 3 (a typical stellar structure). In each picture the bottom line of the frame is a plane of symmetry at which the star collides with its mirror image. The stars collide at their mutual escape velocity. Upper left is the starting configuration; lower left is the situation 25 minutes later, and upper right is the condition shortly after maximal compression, 35 minutes after the start. The last picture, lower right, is 59 minutes from the zero of the first picture. Shaded areas represent densities of 10^{-6} of the original central density or greater, and fluid motion is shown by the length of the arrows, proportional to the velocity at the point from which they emanate. From ref. 14. —FIG. 6

will, in general, coalesce. Figure 6 shows a hydrodynamic calculation by Fred Seidl and A. G. W. Cameron[14] of the head-on collision between two stars. We expect the collision to be highly inelastic because of the strong shocks developed. Dave De Young and Ian Axford[15] have even calculated how these shocks speed up at the "waist" of the collision, ejecting a few percent of the mass at relativistic velocity. Consequently the remaining mass is more tightly bound and the collision is even less elastic than anticipated. Considerations of angular momentum do not restrict the coalescence process for impact radii less than r_s, the stellar radius.

The original calculations of stellar coalescence were for a maximal impact radius for coalescence of $r_s/2$.



COLLISION with negligible interaction. Growth of a massive star, m_2, by coalescence is governed by the conservation of binding energy. In the case shown here the density of the massive star becomes very low, small enough that a compact, dense field star, m_1, can pass right through with negligible interaction. —FIG. 7

But tidal distortion of each star by the other, and the speed-up of the shock wave, which ejects a small mass fraction at high velocity, indicate that this assumption was too conservative. An impact radius for coalescence equal to the star radius is more reasonable.

Coalescence of whole cluster

Lyman Spitzer and William Saslaw have indicated that the collision, and therefore coalescence, cross section is

$$\sigma_c = 4\pi r_s^2\left(1 + \frac{2R_c}{r_s N_c}\right) \text{cm}^2$$

On the other hand the cross section for cusp evolution is given by

$$\sigma_e = \frac{\sigma_r}{20} = \frac{1}{20}\,\frac{12\pi}{(2/3)^{1/2}}\left(\log\frac{N_c}{2}\right)\frac{R_c^2}{N_c^2}\ \text{cm}^2$$

For $10^8 \leq N_c \leq 10^{10}$, which is the present range of interest, $\sigma_e \approx 47\,\frac{R_c^2}{N_c^2}$ cm^2. A straightforward equality between coalescence and evolution cross sections indicates that

$$\frac{N_c}{R_c} = \frac{1.04}{r_s}$$

Compared to the disruption condition this relation shows that all stars would undergo collisions twice when the mean energy of the collisions was one third of that required for disrupting the individual stars. However, the production of massive stars occurs considerably earlier and at lower energy than this for two reasons.

Stellar growth and fluctuations

As the binding energy is roughly the same after each coalescence, $m\,G/r$ is approximately constant. Thus m is proportional to r, and $\sigma_c \approx m^2$. Here

$$\frac{dm}{dt} \approx m^2$$

$$m_2(t) = \frac{m_1}{m_1/m_2(0) - t/\tau_g}$$

and $\tau_g = 1M_\odot$ growth time.

Therefore either an initial few massive stars (O and B stars) 2–5 times the sun's mass will rapidly grow to large size, or, after the first few coalescence collisions, these few coalesced $2M_\odot$ stars grow to completion well ahead of the main distribution. Neglecting the possibility of an initial few massive stars a fraction f of the first-generation $2M_\odot$ stars grows to completion in $\tau_g/2$ or a fraction, roughly τ/τ_g, will reach completion if $\tau < \tau_g/2$. Completion, as we will explain later, occurs at roughly $50M_\odot$ so that the cluster will be transformed into massive stars in a time for which $(\tau/\tau_g)^2 = 1/50$, or roughly when one seventh of the stars have undergone initial coalescence. This reduces further the mean energy of collisions for coalescence by the factor of 1/7 and so ensures coalescence to massive stars at an epoch long before disruptive collisions can take place.

Limiting massive star

The limiting size of the massive stars is set by the condition that the thickness of the massive star (ρ_r proportional to m/r^3, r proportional to $1/m$) cannot become so small that the average field star passes through without capture (figure 7). This size turns out to be roughly 50 $M_\odot$.

The evolution time of massive stars to the end point of nuclear synthesis, and hence supernovae, is much more rapid than small stars like the sun and is roughly 10^6 years. Once coalescence starts it should proceed to completion in roughly τ_r because of the large kinetic-energy loss due to stellar collision. The final coalescence rate will be faster than the initial rate because of the massive stars and also because of the energy loss in collisions. These various factors result in a final coalescence rate

$$\tau_c \approx 2 \times 10^{-11}\,N^2 \text{ years.}$$

The maximal supernova rate occurs when this time equals the evolution time of the massive stars, so that the extremum condition for producing supernovae is $\tau_c = 10^6$ years. The appropriate conditions for this case are summarized in table 2.

If we extend this model to Seyfert galaxies, we observe a radius of the central stellar concentration equal to 3×10^{19} cm; giving the conditions of table 3. In other words the observed size of the central region of the Seyfert galaxy agrees with our theory.

Gas cloud

We can estimate the density of the gas cloud in equilibrium with these supernova explosions and formed by the frequent stellar collisions by noting that the mean kinetic energy of the supernova ejecta (5×10^{18} ergs/gm) is very large compared to the gravitational binding energy of the star clus-

Table 2. Model of Quasistellar Objects

Total number of stars N	$= 2 \times 10^8$
Average mass of stars	= sun's mass
Radius R	$= 10^{18}$ cm
Stellar velocity V_s	= 800 km/sec
Coalescence time τ_c	$= 10^6$ years
Supernova rate	= 5 per year
Average supernova mass	= 50 times sun's mass
Energy rate	$= 5 \times 0.2$ sun masses c^2/year $= 10^{47}$ ergs/sec

Table 3. Model of Seyfert Galaxies

Total number of stars N	$= 6 \times 10^9$
Radius R	$= 3 \times 10^{19}$ cm
Stellar velocity V_s	= 800 km/sec
Coalescence time τ_c	$= 10^9$ years
Supernova rate	= 0.2 per year
Energy rate	$= 3 \times 10^{45}$ ergs/sec

ter, 2×10^{15} ergs/gm. Therefore a very few supernova explosions would be adequate to remove the bulk of the gas cloud. The condition that the gas cloud would not be expelled is that the radiant energy of the collision between gas and supernova ejecta escapes by radiation diffusion faster than it is generated. As the ejection velocity is of the order $c/10$, this condition requires that the gas cloud be no thicker than several photon Compton-scattering mean free paths. (At this low density other sources of opacity are negligible.) We then have a gas density for quasistellar objects, $\rho_g = 2 \times 10^{-17}$ gm/cm^2, and for Seyfert galaxies, $\rho_g = 6 \times 10^{-19}$ gm/cm^2. The quasistellar-object gas density is in good agreement with observation, as determined by the ratio of spectral lines, but the Seyfert-galaxy gas density is ten times larger than observed.

Luminosity and line emission

The continuum optical luminosity arises because of the collisional heating of the expanding supernova envelope by the ambient gas. This effect gives a peak of 10^{46} ergs/sec for a quasistellar object and 3×10^{43} ergs/sec for the observed Seyfert-galaxy gas density. The minimal fluctuation times are days and several months respectively. It is interesting that the Seyfert-galaxy continuum should be only slightly greater than the usual peak supernova luminosity, 2×10^{43} ergs/sec (presumably[16] arising from the beta decay of nickel 56) and should therefore be observable.

The optical lines should arise from the excitation of the whole gas cloud and therefore, as observed, not be subject to the rapid fluctuations characteristic of the continuum radiation from the supernova-envelope collisional heating. When a low-density gas is excited into emission the major fraction of the line emission arises from a relatively few resonant ground-state transitions. The large self-absorption in the center of such lines broadens them, by truncation at the black-body limit, by a factor of ten beyond the normal Doppler width. The absorption lines, on the other hand, are not additionally broadened in this way; so, as expected, the absorption lines are a factor 5–10 narrower. The mean shift between emission and absorption lines in some cases indicates a gas expansion velocity of 10^8 cm/sec, in good agreement with that expected for the mean gas-cloud emission. However, as Geoffrey Burbidge has often emphasized, these remarks do not explain the other cases of absorption lines seemingly unrelated to the emission red shifts that in some cases cluster around the red shift $z = 1.95$.

Infrared emission

The greatest difficulty with any quasistellar and Seyfert-galaxy theory is the extraordinary large emission in the infrared (figure 2), which is ten times larger than the optical emission.

One simple explanation is that these objects are surrounded by large clouds of dust similar to some successful models of planetary nebulae. The dust-cloud emission is excited by ultraviolet emission from the hot gas cloud and an energy balance is easily achieved.

If, on the other hand, the infrared emission varies in time—on the short time scale of a week as observed for the millimeter radio emission—we will have to reject the dust-cloud hypothesis because the size of the dust cloud surrounding the object far exceeds the limitation of light traversal within a fluctuation period.

An alternative explanation for infrared emission as well as millimeter waves is based upon the scattering of photons within a plasma excited into oscillation by two-stream instability.

The details are too complicated for presentation here, but the salient feature is that the high-energy fraction (greater than approximately 30 MeV/nucleon) of the supernova ejecta excites a weak two-stream instability in the ionized gas cloud. Even a very weak excitation of plasma waves represents a highly nonthermal distribution, and the resulting cross section for photon scattering with a change of frequency equal to $\pm\, \omega_p$, the plasma frequency, becomes extraordinarily large. The cross section becomes so large, in fact, that the photon may make $N_s \approx 10^{13}$ scattering events in crossing the plasma. By diffusion theory, the final photon energy escaping the region then becomes approximately $\omega_p (N_s)^{1/2} = 3 \times 10^{13}$ Hz, near the peak of the infrared. The photons take energy from plasma oscillations that, in turn, are fed by the counter-streaming instability. The final limitation is the kinetic energy of the supernova.

The decisive observation requires further infrared monitoring of quasistellar objects.

Finally we should question the basic assumption of an ultradense stellar cluster. The angular momentum implied in Table 2 for the ultradense stellar cluster is 10^{-5} that of a typical galaxy center. On the other hand, the space density of quasistellar objects is roughly 3×10^{-6} that of the average galaxy. If we make the plausible assumption of an initial uniform distribution of angular momenta, for angular momenta small compared to some mean value (presumably that of a typical galaxy), the extremum required for a coalescing cluster is consistent with the observed frequency of quasistellar objects.

Indeed any such theory can always enjoy a moment of triumph before being confronted with the next observation: quasistellar theories being more susceptible than most—"shedding the erudite verbal haze . . . and demolishing the theory that Jack built."

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