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QUASARS AND EXPLODING GALAXIES

A Lecture by

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The vast majority of galaxies are orderly, law-abiding citizens of the Universe. But every community has its offenders, and the Universe, too, has some inhabitants which are disturbed, delinquent or just downright violent. Their numbers are were small. But because these 'active' galaxies (as they're generally called) are amongst the brightest and most powerful in the Universe, they positively shout out to be investigated.

Astronomers hardly had time to get used to the idea of 'normal' galaxies before the first of the 'active' variety reared its dazzling head. A young astronomer called Carl Seyfert, working in the USA in 1943, drew attention to a small number of spiral galaxies - about a dozen - which seemed to be behaving in a pretty strange way. At first he had thought that their spiral arms were very faint, but he then realised that this was simply a contrast effect - the centres of these galaxies were in fact unusually bright.

As well as being so bright, their centres looked very odd, appearing as tiny, starlike points instead of the well-developed central bulges of most spiral galaxies. Intrigued, Seyfert took spectra of his galaxies. He found the cores of these galaxies did not show the spectrum of a mass of stars, but were dominated by the spectral lines of hot gas, rushing around the centre with considerable speed.

Because they were such an anomaly at the time, no one else joined Seyfert in his researches into these strange galaxies. His findings remained practically unknown until the early 1960s, by which time astronomers, having come across many more inexplicable galaxies, had resorted to ploughing through past literature. Seyfert himself had died just beforehand, but astronomers honoured his memory in giving his name to this whole new class of galaxies.

The several hundred Seyfert galaxies now known are basically giant spirals like our own, but they have cores (or nuclei) which are extremely disturbed. Hot gas at 20,000°C (36,000°F) sweeps about the brilliant nucleus with speeds of up to 7,000 kilometres per second (that's 16 million miles per hour!). Sometimes, the disruption has spread to the outer parts of the galaxy. The Seyfert galaxy NGC 1275, with its outward-moving filaments of gas, looks like a gigantic version of the Crab Nebula.

The core itself gives out a tremendous amount of energy over the whole range of the wavelength spectrum. Its light output dominates the rest of the galaxy, and the same is true for the X-rays and infrared radiation it produces. A few Seyferts give out radio waves too. All of this points to the core being a site of violent and extreme conditions; it is the 'powerhouse' which gives energy to 'a dragon in the middle' .

Astronomers would like to know what the dragon *is*. They know that it is small, for the entire disturbed region surrounding it is only a few tens or hundreds of light years across. But the very degree of its smallness came as a surprise, bringing with it the first of many energy problems that were to confound researchers investigating active galaxies.

The initial difficulty is that the core is too small for any telescope to photograph. Just as in the case of a bright star, the continual shifting of our atmosphere smears out its point-like image into a much bigger disc which has nothing to do with its *actual* size. But astronomers 'hunting the dragon' got help in their search from a totally unexpected quarter: old star catalogues. Photographic catalogues made around the turn of the century had erroneously classed some of the brighter Seyfert galaxies as stars. All that the earlier catalogues could see was the brilliant, starlike core without the faint extensions of the surrounding galaxy, and their mistake was perfectly understandable. What was particularly interesting was that many of these 'stars' had been classified as variable, changing irregularly in brightness by a factor of two over a period of a few months to a year.

Measure the time for an object to change in brightness, and you can get an estimate of its size. Imagine a glowing ball of gas, measuring a light year across. Now think of it being abruptly 'switched off'. The ball itself won't go dark immediately, however, because light itself takes time to fade away across it. The surface closest to you will go dark first, but it won't be until a year later that the back surface - a light year further away - will fade. In other words, a light source can't change in brightness any more quickly than the time it takes light to cross it.

If the nuclei of Seyfert galaxies can vary in brightness on timescales of a few months, it means that they must be only light-months across. This really is tiny on the scale of a galaxy, and more comparable with the scale of our solar system (Pluto's orbit spans eleven light-hours). Some nuclei may be even smaller than this. There's one whose X-ray output, as monitored by the orbiting Einstein Observatory satellite, varies on a timescale of 2½ minutes. This means that a significant proportion of its energy is coming from a region less than half the size of Mercury's orbit about the Sun.

The size of the core would be no problem if it weren't for the energy it generates. Seyfert galaxies lie nearby, and it's relatively easy to measure their distances and convert the apparent brightness of their cores into real luminosities. This luminosity corresponds - very nearly - to the total energy of a typical galaxy like ours packed into a region a few sizes larger than our Solar System.

Faced with an energy problem like this, the reaction of many early-1960s' astronomers was to hope it would go away and lose itself. Only, it didn't. It actually got worse, as subsequent discoveries highlighted galaxies with even greater reserves of power.

Before we face these galaxies - the most violent in the Universe - there are a few ends to be tied up. The Seyfert galaxies we see are highly energetic at the moment, but they couldn't possibly have kept up this profligate output for any more than a small fraction of their lives. Otherwise, there would be no galaxy left to see! This means that Seyfert activity must be intermittent. The question is: how frequently does it happen?

Earlier on, we mentioned that Seyfert galaxies are, by and large, giant spirals. In fact, one in ten of all giant spirals is a Seyfert. We can turn this statistic around to ask: is it possible that *all* giant spirals spend one part in ten of their lives undergoing Seyfert outbursts? In particular, has *our* giant spiral spent ten per cent of its lifetime like this? The available evidence suggests that it has.

Seyfert activity almost pales into insignificance as we ascend the ladder of extragalactic violence. On the next rung up, we find the galaxies whose identification, in the 1950s, helped to unearth Seyfert's forgotten spirals. These radio galaxies were different again. They give out as much energy in radio waves as they do in light, and some of them are tremendously powerful. The radio galaxy Cygnus A is actually the second brightest radio source in the whole sky - yet it lies well outside our Galaxy!

Radio and optical astronomers collaborated in an attempt to pin down the kind of object which could emit radio waves thousands of times more strongly than any normal galaxy. Co-operation between the two camps was a little strained to begin with. For a start, it was found that a few radio astronomers, trained as pure physicists, were plotting their sky co-ordinates back-to-front in what appeared to be a more logical way! But co-operation eventually paid off. A handful of most peculiar-looking galaxies were isolated as sources of the radio waves, and the optical astronomers began their crackdown to discover what kinds of galaxies these were.

Cygnus A was typical. It was clearly very distant, but showed a distinctly double shape, like a pair of galaxies colliding with each other. Perhaps *this* was the origin of their powerful radio waves? Then maybe there would be other signs of such a titanic disturbance, such as streams of hot gas. Leading observer Walter Baade had a hunch that a spectrum would show these up. His long-time colleague Rudolph Minkowski was equally adamant that Cygnus A was not a pair of colliding galaxies, and predicted that hot gas wouldn't be detected. The men made a famous bet together with a bottle of whisky as the stake. Baade spent all night on the 200-inch Palomar telescope (now called the Hale 5-metre) in an attempt to secure the spectrum of the dim and distant galaxy, or galaxies. He got his bottle. There on the spectrum were the tell-tale emission lines from hot, excited gas: proof at last that radio galaxies were galaxies in collision.

Baade's hunch was a good one; but unfortunately, it was wrong. Other astronomers were not slow to realise that a pair of colliding galaxies could never unleash as much energy as radio galaxies do. As we now know, galaxy collisions are fairly peaceful affairs.

Our present ideas about radio galaxies are likely to be much nearer the mark. It's not because scientists are any more brilliant, but a result of changes in the pattern of science over the past few decades. Ironically, increasing specialisation in science has led to more co-operation between scientists of all disciplines, perhaps in an unconscious attempt to preserve the overall picture. International science today means sharing facilities, whether computers, telescopes or simply ideas bounced between participants at conferences and 'workshops'. Astronomers don't tend to put labels on themselves any more. Instead of being 'optical astronomers' or 'radio astronomers', they're all physicists who use the Universe as their laboratory.

Nowhere has the spirit of co-operation been more marked than between the observers and the theorists. It's fair to say that much of today's revolution in astronomy has been brought about by observers and theorists working hand-in-glove, each group spurring the other on. It wasn't always so. Observers have traditionally been suspicious of scientists who seemed to deal in esoteric concepts and with scant regard for reality. But time and time again, whenever observers found something new and inexplicable they also found that the theorists had been quietly, and independently, working away on the same problem. After the round of convincing explanations for the expanding Universe, the microwave background and pulsars, observers and theorists realised that their interests were best served in joining forces. As leading theorist Tommy Gold said in an after-dinner conference speech in 1963, welcoming relativity specialists to the astronomers' camp: 'It was ... [Fred] Hoyle's genius ... that allowed one to suggest that the relativists with their sophisticated work were not only magnificent cultural ornaments but might actually be useful to science!'.

Theorists and observers alike agree that radio galaxies are a still-more powerful version of an exploding galaxy. The galaxies responsible for the immense radio output often look disturbed, sometimes slashed with dramatic swathes of black dust generated by their outbursts. Many of them contain streams of gas moving with speeds in excess of 6,000 kilometres (3,700 miles) per second. But for most, the hallmark of their violence is located in the regions that generate their radio waves. Almost all galaxies emit some radio waves, but these come from the galaxy itself, from the gas which lives between the stars. Radio galaxies are quite different. Although some radio emission arises in the main body of the galaxy, most of it comes from two gigantic lobes of gas which straddle the galaxy in a roughly symmetrical way. These clouds have been somehow 'beamed out' by the nucleus of the galaxy, a sure sign of explosive activity. A large number of radio galaxies have jets of matter - sometimes visible optically - spurting up to three million light years from their nuclei into the radio-emitting lobes. 'Such jets have become common, almost ubiquitous' say Martin Elvis and Andrew Wilson, writing in the scientific journal *Nature* on discoveries reported at a recent conference on radio galaxies.

Like Seyferts, the radio galaxies pose considerable problems when it comes to their energy supply. Somehow, they are able to spew out matter from their cores at a tenth the speed of light - and not just in large quantities but out to considerable distances, too. Many radio galaxies have clouds which span more than a million light years. The present record holder is a galaxy called 3C236 (the 236th source in the Third Cambridge Catalogue of radio sources), whose clouds cover an astonishing 18 million light years - some nine times the distance between the Milky Way and the Andromeda Galaxy. Even so, it mightn't be the biggest of all. Some radio astronomers believe they have detected extended clouds around a few otherwise moderately large radio galaxies - and 3C345, the biggest of all, could be 8 million light years across!

The clouds themselves can give some clues about the powerhouse at the centres of radio galaxies. By measuring the amount of energy they give out at different wavelengths, radio astronomers can plot an 'energy spectrum' to find what makes the clouds glow. They have discovered that the radio waves are emitted by tiny, negatively-charged electrons, which have somehow been accelerated to velocities close to the speed of light. When these fast moving particles meet the weak magnetic fields of intergalactic space, they are forced to spiral around the field lines and give out their energy in the form of synchroton radiation - so-named because it was first detected in powerful synchrotron particle accelerators on the Earth. The energy is emitted at radio wavelengths, but in some radio galaxies it is so intense that the clouds can be faintly seen glowing at optical wavelengths too.

The clouds' shapes reveal still more about these strange galaxies and their surroundings. Quite often, their structure is very complicated, with powerfully-emitting 'hot spots' marking where the beam is still feeding energy to the cloud. Some galaxies' twin clouds have been practically swept back and merged into a trailing tail as the galaxy has moved through the relatively dense gas in a cluster of galaxies. These look irresistibly like squirming tadpoles, and the name 'tadpole galaxy' has stuck.

Most important of all, many radio galaxies are surrounded by more than one cloud system. This is firm evidence for repeated activity, with the larger clouds produced by an earlier burst of energy than those closer to the visible galaxy. These nested-cloud galaxies tell us that the bursts of activity which produce the clouds last for a few million years. After such an outburst, the parent galaxy becomes dormant for 100 million years or so. Then something triggers the central powerhouse to repeat the act all over again. It is astonishing that, despite the 100 million years dormancy, the repeat outburst occurs in almost exactly the same direction as its predecessor. When it comes to tracking down the nature of the powerhouse, it's this sort of evidence which gives the theorists something to bite on.

What kind of galaxy suffers convulsions such as these? The only sort which can generate activity on this scale are giant elliptical galaxies with the power to muster a huge concentration of mass towards their centres. Many of the galaxies lurking at the heart of rich clusters are powerful radio galaxies, possibly as a result of the gas fed to them by their cannibal life-style. Less easy to understand are strong radio galaxies, like the devastated Centaurus A, that live completely alone. What's certain, however, is that there's no chance of our Milky Way turning into a radio galaxy. Spirals are too small ever to develop the extreme central densities that a radio galaxy's powerhouse evidently needs.

Even the violent radio galaxies are dwarfed by the quasars. These strange objects - insignificant to look at, and yet incredibly powerful - are still giving astronomers headaches more than 30 years after they were first identified. The quasar story began in the same way as the hunt for the radio galaxies, when radio astronomers located a number of powerful sources of radiation in the sky. But this time, try as they might, the optical astronomers just couldn't find the culprits responsible. Every time, the relatively imprecise radio position was occupied by a field of thousands of apparently ordinary stars. There was no dust, no gas and nothing noticeably peculiar.

The astronomers, in desperation, turned their attention to the myriad of faint stars covering the radio position. They carefully checked out every one for signs of abnormality and at last their patience paid off. In each field were one or two stars which were definitely too blue to be 'normal'.

The next stage was to get spectra of these stars, to check on their temperature and composition. There is no reason *why* a star should give out powerful radio waves, and so the puzzled astronomers were expecting a very strange kind of spectrum indeed from these mystery objects. But they were totally unprepared for what they got: in every case, a spectrum of an evidently very hot object, crossed by spectral lines that couldn't be pinned down to any known chemical element.

The astronomers of the early 1960s were totally baffled. The objects were discussed at the December 1960 meeting of the American Astronomical Society, and the conclusion astronomers reached about 3C48 - one of the mystery stars - was that 'there is a remote possibility that it may be a distant galaxy of stars; but there is general agreement among the astronomers concerned that it is a relatively nearby star with most peculiar properties'.

Nature co-operated to confirm that at least one 'quasi-stellar object' (or 'crazy stellar object', in the words of the young daughter of astronomers Margaret and Geoffrey Burbidge) was definitely the source of strong radio waves. In 1962, the Moon conveniently passed in front of one of the objects, 3C273, and simultaneously both light and radio waves were cut off. Astronomers could at least relax in the knowledge that their blue stars were leading them along the right trail.

The last instalment of the discovery story involves not so much astronomy, as scientific instinct - the 'aha!', as astronomer Charles Long describes it. When Maarten Schmidt of the Hale Observatories sat down in 1963 to write a report on 3C273, all the jumbled pieces of the puzzle were there, but no one had been able to fit them together. 3C273 looked like a star with a jet coming out of it; it was the brightest of all the quasi-stellar objects (although only magnitude 13), and its spectrum was reasonably clear. Schmidt's subconscious mind must have turned to that peculiar spectrum again and again. There was something familiar about it: to an expert spectroscopist like Schmidt, an oddly recognisable pattern of lines.

Then he realised. The lines in the spectrum were a part of a well-known series of lines produced by hydrogen atoms, but all shifted to longer (redder) wavelengths. The longest wavelength lines of the series were missing - shifted out of the visible altogether, and into the infrared part of the spectrum by the object's enormous redshift. Schmidt measured the redshift and found it to be 0.158, corresponding to a recession velocity of 15.8 per cent of the speed of light and - from Hubble's redshift-distance law - a distance of 2,000 million light years. The 'star' was as distant as the most remote galaxies known. And judging from its apparent brightness, it was much more luminous.

The other quasi-stellar objects (a term mercifully shortened to 'quasars') turned out to have higher redshifts still. That of 3C48, the subject of discussion at the 1960 AAS meeting, came to 0.3675, placing it 4,500 million light years away with a recession velocity of 36.75 per cent of the speed of light. The highest quasar redshift yet measured stands at almost 5. This quasar is rushing away at over 90 per cent of the speed of light and lies at a breathtaking distance of 13,000 million light years.

Today, over 1,500 quasars have been found. The majority, as it happens, do not emit radio waves, making their original discovery and identification something of a lucky accident. With a few exceptions, they look exactly like faint stars. It is only their enormous redshifts - and in some cases, strong infrared and X-ray emission - which give them away.

Beneath a quasar's undistinguished facade lurks one of the Universe's most potent power generators. Energy is packed into the quasars to a truly astonishing degree. Like Seyfert galaxies, many quasars vary in their light output, which, as we have learnt, tells us something about the size of the source. But these celestial beacons can change in brightness by a factor of ten, in just a matter of months, while their close relatives, the BL Lac objects, sometimes flare up to become a hundred times brighter over the same kind of period. X-ray astronomers report that some quasars flicker on timescales of seconds. This all points to quasars being extremely small. They cannot be much larger than our Solar System, but within that minuscule region they pack the total energy of no less than a hundred galaxies. Energy is concentrated to an extent a million, million, million times greater than it is in any part of our Milky Way Galaxy. It scarcely sounds believable. And this was exactly the reaction of many 1960s' astronomers to this outsize energy problem. Even today, there are some who still strive desperately to make it go away.

One way of killing the energy problem at a stroke is to postulate that the quasars are nearer to us. Their size won't change - their short variability timescale still puts them in the solar system size class - but their energies will. If they are nearby, they don't have to be nearly as luminous. But surely their enormous redshifts automatically consign them to vast distances? This, argued some astronomers, supposes that the redshifts of quasars are due to the expansion of the

Universe - but quasars are such peculiar objects that it's possible that even their redshift has some other origin. Isn't it just as likely, they suggested, that quasars are nearby objects with high redshifts produced by physical processes *inside* them?

One idea could be scotched very quickly. It was possible that quasars were fast-moving objects ejected from galaxies, and their redshifts arose from their high speeds - but in this case we would expect to find some blueshifts too, and quasars never show a blueshift. The only other serious alternative is that the redshift of quasars is due to their gravity. Light, as a form of energy, is affected by gravitational fields in the same way that material bodies are. To escape from any gravitational field, a body has to use up energy: the stronger the field, the more energy has to be expended. In the case of light, the energy used shows up as a redshift, and the stronger the gravity, the greater the redshift. Light from dense, high-gravity stars like white dwarfs shows a marked gravitational redshift. So perhaps quasars are dense objects which lie nearby and there is no excess energy problem to explain? Or does an explanation of their redshift require some 'new physics', as a few astronomers have ventured to suggest?

The 'local quasar' astronomers, although more vociferous in the 1960s, have scored some apparent victories in the past few years. They point to some quasars apparently spewing out blobs of matter with several times the velocity of light - something which contravenes the theory of relativity. This problem is removed if quasars lie close at hand. Ace quasar-hound Halton ('Chip') Arp has highlighted several alignments of quasars in the sky which he claims add weight to his 'local ejection' hypothesis. In addition, Arp has spent the last two decades looking for physical connections between obviously nearby galaxies (of low redshift) and quasars (of high redshift). He reports a greater-than-expected incidence of quasars near galaxies and close quasar galaxy pairs - and in each case, the galaxy and quasar have wildly different redshifts. In a few cases, a faint bridge of stars linking the two seems dimly discernible.

It's fair to say that most astronomers feel that Arp is barking up the wrong tree. As we shall see later, there's really no need to make quasars local, or to search for some exotic explanation of their redshifts, for the 'energy problem' can be explained in an elegant and consistent way. But at first sight, the 'local' evidence is persuasive. However, other astronomers have pointed out that the apparent 'faster than light' velocities in quasars - so-called 'superluminal expansion' - can be easily explained by fairly simple geometry. If a blob or jet from a quasar is coming at us almost head-on at a speed close to that of light, detailed calculations show that it will actually seem to move faster than light. As the *Los Angeles Times* somewhat clumsily reported: 'US Scientists Measure Super Velocity of Quasar and Conjecture It Is Illusion'.

Arp's apparent alignments look set to follow the same road. Cardiff astronomer Mike Edmunds has used the University's computer to simulate a random sprinkling of quasars, and finds that fifteen lines of three quasars each will occur by chance in any given region of the sky.

But what of the most persuasive evidence of all - the apparent connections between nearby galaxies and allegedly remote quasars? Once again, the 'traditionalists' have an answer. Some of Arp's 'bridges' have been re-examined using today's improved scanning and computing techniques, and it seems that the majority of them really don't exist. Most are simply contrast effects between two densely-grained and narrowly separated areas of photographic emulsion.

However, it's not that easy to dismiss the apparent clustering of quasars around galaxies. Although it's a very difficult statistical problem to predict how many quasars should be found in any given area of sky, there really does seem to be a marked increase in their numbers close to galaxies - just as if they had been thrown out of the galaxies themselves. But even this puzzling state of affairs can be explained in a conventional, if seemingly bizarre, way.

As we already know, gravitational fields rob escaping light of its energy to produce a gravitational redshift. Gravitational fields can also bend light like a lens, causing almost invisible objects to be intensified into bright, often multiple images. This strange effect is demonstrated *par excellence* in the 'double quasar': two quasars of exactly the same redshift separated in the sky by a distance equivalent to only one three-hundredth the diameter of the Full Moon. The similarity between the two quasars is too good to be true, and astronomers quickly concluded that they were observing the *same* object, split into two by some invisible gravitational lens. Hunch is all very well, but proof didn't come until astronomers using a sensitive electronic light-detector on the Hale 5-metre telescope were able to photograph an extremely faint galaxy lying between the two quasar images. This galaxy lies very much closer to us than the quasar, and its gravitational field focuses its light into two (and probably more) surrounding images.

This peculiar lens effect can explain the concentration of quasars around galaxies, particularly so if the latter have massive haloes. According to George Canizares of the Massachusetts Institute of Technology, 'the focusing can intensify and make detectable quasars which would otherwise have been below the threshold'. In this case, the quasar images aren't split by the gravitational lens, but are simply intensified by it. In regions away from galaxies, the quasars remain as faint as ever.

And so it seems that the quasars really do lie at the distances indicated by their huge redshifts. They really *are* phenomenally distant and uncompromisingly energetic. 'Why fight the evidence?' is the attitude of many scientists. 'Many times in their 20-year history, quasars have been charged with breaking the known laws of physics in one way or another, and each time they have been cleared', says *New Scientist* magazine in their defence.

But just what *are* quasars, anyway? It's a question that has challenged astronomers for many years. Only in the last decade has a consensus begun to emerge, following a concerted attack from many of the world's top-flight scientists who were goaded into action by the quasars' apparent disregard for conventional physics. Astronomy is far from being a field where people simply 'make discoveries'. One of its main concerns is to test whether the physical laws which we know to hold good on Earth also apply in the far more extreme conditions of space. An astronomer uses the Universe as a laboratory more versatile than any he could find here: where he can test the behaviour of matter under conditions of excessive heat and cold, high and low density, ultra-high velocities and on timescales even longer than the age of the Earth. The most tempting and challenging test-beds are those objects, like quasars, which are the most extreme of all.

Alec Boksenberg, former Director of the Royal Greenwich Observatory, is one of the world's leading quasar investigators. Fascinated by tantalisingly remote, but dismayingly faint galaxies and quasars, he has developed an ultimate light-gathering device - the Image Photon Counting System (IPCS) - to wring their feeble light-waves dry of information. Quasars and galaxies yield up their secrets in their spectra, which tell astronomers of their composition and physical conditions. But quasars are so faint that early quasar spectra, recorded on photographic plates, were sometimes prohibitively difficult to decode with confidence. Now astronomers using Boksenberg's IPCS and other, similar electronic gathering systems - far more efficient at recording elusive light-waves than a photographic plate - can watch a minicomputer at the end of a telescope build up a quasar's spectrum in unprecedented detail in 'real time'. The astronomer can interact with the device if he wants to concentrate on any particular feature - perhaps a faint spectral line of special interest. But the real advantage of electronic light gathering detectors lies in their exceptional speed. While in 1929 it took Milton Humason 45 hours on the 100-inch (2.5-metre) Mount Wilson telescope to get a spectrum of a faint galaxy - a task which he had to spread out over five consecutive nights - a modern image tube spectrograph can do the same job in ten minutes!

Sophisticated electronic cameras and subsequent computer image processing have also helped to rob quasars of some of their mystery. A number of the nearer quasars (on the basis of their redshifts) have now been found to be surrounded by a very faint 'fuzz' which appears to be a surrounding galaxy almost totally drowned out by light from the dazzling 'quasar' core. There's a growing body of evidence which suggests that quasars are vastly scaled-up versions of Seyfert galaxies. Husband and wife team Sue Wyckoff and Peter Wehinger maintain that 'If... quasars are high-redshift analogues of Seyfert galaxies, then we should not be too surprised that they appear stellar even on long-exposure photographs'. Only in the very nearest quasars can we pick out the dim galaxy which surrounds the tiny, disturbed nucleus.

Quasars, it now seems certain, are yet another kind of violent galaxy. While their spectra look like those of Seyferts - interrupted by spectral lines arising in hot, fast-moving gas streams - they behave, in some cases, more like a radio galaxy. But they're more powerful than both, and the most luminous objects by far in the Universe.

In all this wanton violence amongst galaxies, there is an underlying pattern. Violence occurs only in galaxy cores, where the density, temperature and pressure are sufficiently high. And violence is closely associated with distance away from us. Nearby galaxies, in the main, are undisturbed - with the exception of the slightly active Seyferts. In the realms of the medium-to-far distant galaxies, we find the badly-disturbed radio galaxies, while awesomely-powerful quasars are found only in the most remote reaches of the Universe.

All this may sound quite arbitrary until we think of it this way: as well as being segregated in space, active galaxies are segregated in time. Because Seyfert galaxies lie nearby, their light takes a relatively short time to reach us and so we see them very much as they are in the present. The light from radio galaxies can take several thousands of millions of years to reach us, and so we see them not as they are today, but as they were thousands of millions of years ago - in other words, when they were quite a lot younger. In quasars, the effect of this 'lookback time' is the most dramatic of all. A quasar 10,000 million light years away will look to us as it did 10,000 million years in the past, a mere 5,000 million years after the beginning of the Universe. Quasars, then, are among the earliest objects we can see - and the most violent.

Piecing together the evidence, astronomers have come to the conclusion that it's not just human beings who are prone to periods of violent behaviour during youth. Galaxies appear to be similarly affected. Far from being a random or unexpected phenomenon, it may be that all galaxies go through an active phase when they are young, and that galaxies which are currently active can tell us something of the way in which most galaxies grow up.

No one has yet seen a galaxy being born. But there's good evidence that they begin their lives as vast gas clouds which collapse ever more swiftly under the relentless pull of gravity. And at the centre, contraction occurs fastest: so quickly and dramatically that the young galaxy's core collapses in on itself to become nature's surest gravitational trap - a massive black hole.

A 'galaxy-mass' black hole is on a totally different scale from those created in stellar explosions. Depending on how much matter there is available in the 'protogalactic' gas cloud, a young galaxy may be able to 'grow' a central black hole up to thousands of millions of times the mass of an average star. It continues to grow, as fodder from the still-collapsing galaxy pours in. But young black holes are messy eaters, and not all the material is gobbled up at once. The residue collects in a vortex-like 'accretion disc' surrounding the hole, glaring and flickering fitfully as its globs of gas sweep around at speeds close to that of light before they're swallowed up forever.

The accretion disc glows fiercely, giving out alarming quantities of energetic, short-wavelength radiation. It's probably this flaring beacon that we call the core of a Seyfert galaxy, or a quasar. But the accretion disc does more than just glare. It is the 'dragon' at the centre of the galaxy; one of the most potent generators of power known in nature.

On the present scenario quasars are the accretion discs at the centres of young massive galaxies. These swirling discs generate powerful shockwaves which send gas clouds hurtling through the young galaxy, but they can act in a more organised way too. Brilliant Cambridge theorist Martin Rees has demonstrated that a massive black hole and accretion disc combination can shoot beams of highly energetic particles along its axis of rotation until they end up as huge clouds which straddle the galaxy in space.

Although all quasars appear to have a 'dragon', only a few are surrounded by clouds. It may be that this is a late stage in a quasar's development. But it seems to link it to the next phase in the life of a massive elliptical galaxy, that of a radio galaxy.

Are radio galaxies actually dead quasars? As we've seen, the links seem strong, and radio galaxies certainly have disturbed or slightly active cores. Many have beams emanating from their cores which feed the surrounding clouds. And the orbits of stars near the centre of at least one radio galaxy seem to be governed by the presence of some unseen mass more than 5,000 million times the mass of our Sun. But it's the repeated activity in radio galaxies which points to a black hole at work. As we saw earlier 'explosions' in radio galaxies are separated by hundreds of millions of years, and yet even after this length of time, the core appears to 'remember' the direction of its previous outbursts. At the moment the only contender for the title of 'cosmic elephant' is an accretion disc. When sufficient material falls on to it, the disc is triggered into beaming along its axis of rotation - which always points in roughly the same direction.

Radio galaxies, too, must die. Leading optical astronomer Jim Gunn points out that there are enough problems involved in 'feeding the monster' at the centres of these notoriously gas-free galaxies anyway - and the day must come when the accretion disc can be fuelled no more. It's on the cards that some nearby giant ellipticals could well be dead radio galaxies, which, in their profligate youth, were quasars.

Seyfert galaxies are the poor country cousins of quasars and radio galaxies. As less-massive spiral galaxies, they were never able to develop the truly heavyweight black holes which may lurk at the hearts of their elliptical counterparts. As a result, their acts of violence have always been more limited; although their cores can generate shockwaves, they were never powerful enough to beam effectively. But because Seyferts are gas-rich spirals, the 'dragon' still has food, and activity, albeit mild, still continues today. Even, perhaps, in our own galaxy.

The last word goes to dragon-inventor Daniel Weedman: 'We have... an incredible phenomenon that can range over a factor of a million in luminosity without changing its properties... the inference... is that the quasar phenomenon is an event in a galactic nucleus, low-luminosity examples of which are given by the Seyferts.'

At first sight, a fascination with galactic violence might seem a rather macabre preoccupation for the best brains in the astronomical community. But as we have seen, it's one of the most challenging areas of astrophysics, and a decisive test-bed for physical laws. It tells of the birth and evolution of galaxies, of matter and radiation in the most extreme conditions, and of the harrowing violence of our early Universe. As we, the products of a calm, mature Universe contemplate the serenity of our surroundings, those tranquil galaxies upon which we rest our gaze may well be relishing fond memories of a turbulent youth.

GRESHAM COLLEGE

Policy & Objectives

An independently funded educational institution, Gresham College exists

- to continue the free public lectures which have been given for 400 years, and to reinterpret the 'new learning' of Sir Thomas Gresham's day in contemporary terms;
- to engage in study, teaching and research, particularly in those disciplines represented by the Gresham Professors;
- to foster academic consideration of contemporary problems;
- to challenge those who live or work in the City of London to engage in intellectual debate on those subjects in which the City has a proper concern; and to provide a window on the City for learned societies, both national and international.

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