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Active Galaxies: Overview

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Active Galaxies: Overview

Defining an 'ACTIVE GALACTIC NUCLEUS' (AGN) can be difficult. The last two words are relatively simple, as an AGN is an energetic event which is *never* found anywhere in the universe except within the central parsecs of a galaxy. This is not surprising, because any dynamical friction should soon force any very massive compact object to settle down into the center of the galactic gravitational potential.

A GALACTIC NUCLEUS is said to be 'active' if it generates a 'substantial' (or detectable) amount of energy by processes different from those found anywhere else in galaxies. That is, the energy of the 'activity' is not produced by evolution of stars and interstellar matter. This definition is clean because it is theoretical. The actual observational task of identifying AGN can be messy, especially when the nonstellar activity is weak compared with the background of normal stellar processes, including birth and death. Classifying AGN meaningfully is harder. Understanding their physical nature is harder still.

The problems are further complicated because the nonstellar activity releases energy in many forms, and at photon wavelengths covering nearly the entire electromagnetic spectrum. Since observing instruments and methods differ markedly from one waveband to another, many overlapping wavelength-specific classification schemes and models have been proposed.

Not surprisingly, astronomers became aware of the more spectacular and luminous examples of AGN first. These nuclei were sufficiently luminous that they could outshine the entire galaxy in which they resided. They were also very distant, and it was often not possible, before very sensitive imaging had detected the surrounding galaxy, to distinguish their optical appearance from that of a star. This led to their designation as 'quasistellar' objects. Some of the first of these were also powerful radio sources, and the term was soon abbreviated to 'quasar', which now generally refers to all high-luminosity AGN (see QUASISTELLAR OBJECTS: OVERVIEW). Their unique nature became more obvious when studying their spectra, in almost any wavelength region.

These unique properties have now been found in active nuclei spanning an extraordinary range in luminosity[1]. There are only surprisingly subtle spectroscopic differences between a quasar with a luminosity of 10^{48} erg s^{-1} and what had previously been identified as a 'Seyfert galaxy nucleus' of luminosity 10^{42} erg s^{-1}. The evidence is overwhelming that these two astronomical categories must have a single common physical explanation. Thus today, hardly any distinction is made between 'quasar' and 'Seyfert 1 nucleus', as their main difference is (somewhat arbitrarily) in their luminosity. It follows that this overview of AGN should be supplemented by reading the accompanying chapters on quasars in this Encyclopedia.

[1] The vast range of AGN luminosities, much larger than what is seen in stars for example, is one of their outstanding features.

Understanding The Central Engine in AGN

There are several key ideas which are being used to organize and make sense of our large and growing observational information about AGN.

Unified Models

Since the earliest AGN studies, it was recognized that they can show strong observational differences in spite of many other similarities. Two characteristics seem to have a sufficiently bimodal distribution to justify using them to divide AGN into two pairs of classes: strong radio emission (which distinguishes radio-loud (RL) from radio-weak (RW) AGN) and broad permitted line emission (which distinguishes type 1 Seyfert nuclei from type 2). A more extensive discussion of these ideas is given in ACTIVE GALAXIES: UNIFIED MODEL and ACTIVE GALAXIES: VARIABILITY.

The majority of quasars are only moderately stronger radio sources than normal galaxies. (They are sometimes referred to as radio-quiet (RQ) AGN, although strictly speaking they do emit some radio flux so that RW is a more accurate description.) An important minority of quasars are well known for the beams of high-energy particles they accelerate. The radio emission from these jets is nearly always bipolar—a key indicator that the central engine can have axial symmetry. In many models, this jet–lobe axis is the spin axis of the central massive black hole. In the most dramatic subsample of RL AGN, the 'blazars' (loosely named after the prototype object BL Lacertae), the highly polarized, violently variable, steep red continuum was identified as nonthermal synchrotron emission. Blazar is an informal term used to encompass the prototypical nonthermal BL Lacertae objects (with very weak emission lines) as well as the optically violently variable quasars. Interferometric maps showed that the core-dominated radio emission generally had a one-sided jet, which often appears to be expanding at apparent transverse speeds several times larger than c. The most extreme of these objects appear to emit a substantial fraction of their energy in the gamma rays, and possibly even up to TeV energies. All of these remarkable (and manifestly nonstellar) blazar properties were soon understood as the result of viewing a relativistic jet (of electrons and either protons or positrons), which is emerging from the active nucleus close to our line of sight. This nearly 'pole-on' viewing angle produces several relativistic effects such as Doppler boosting of the 'beamed' synchrotron emission and a compression of apparent timescales which accounts for 'superluminal motion' without violating special relativity. The one-sided nature of the innermost jets is usually attributed to 'Doppler favoritism'. If there is currently an outflow in the opposite direction (which is predicted by some theoretical models, but not yet confirmed), it is invisible because Doppler de-boosting makes it thousands of times fainter.

An immediate consequence of the beaming explanation of core-dominated RL AGN is that more AGN with radio jets must be pointing away from Earth. These must be detectable by their isotropic emission (lines or extended radio lobes), as either lobe-dominated RL AGN, or perhaps

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'radiogalaxies' (whose optical properties can be Sefyert 2s or even low-ionization emission line regions (LINERs)). The (unbeamed) emission lines may or may not be detectable but are harder to detect over the glare of the amplified nonthermal jet continuum.

These studies proved that the central engine in AGN (the RL ones, at least) have a strong bipolar symmetry which has been preserved over millions of years or more in the largest double-lobe radio sources. They also proved that the observational appearance of RL AGN can depend dramatically on our viewing angle. However, it is not yet certain how completely these same insights may be transferred to the majority of AGN, which are RW.

Broad permitted emission lines are usually taken as one of the defining characteristics of AGN. They arise from high-density photoionized gas. Their high ionization state and large velocity range both indicate that they arise in a 'broad line region' (BLR) relatively near the central engine. However, for every broad-emission-line AGN of a given luminosity (classified as a 'Seyfert 1'), there is at least one galactic nucleus which might otherwise be classified as a Seyfert, but which lacks broad line emissions and is classified as a 'Seyfert 2'. In the Seyfert 2s it is difficult or impossible to view the central engine, and its surrounding BLR, directly. In a minority of cases, strong evidence for the central engine is present, in the form of either a highly absorbed ($N_H \sim 10^{23}$ cm^{-2}) hard-x-ray continuum source or broad Balmer emission line wings seen in the spectrum of linearly polarized light.

Less direct evidence is the detection of fluorescent emission from the x-ray Kα line at 6.4 keV. In some Seyfert 2s, the very large equivalent width of this line (about an order of magnitude larger than in unobscured Seyfert 1s) is interpreted as being powered by a nuclear hard-x-ray source, virtually none of which is visible along our direct line of sight to the nucleus. A similar argument has been made from UV spectroscopy: adding up all the ionizing photons inferred from the UV continuum seems to be inadequate to account for all the Seyfert emission line flux detected, and especially for the infrared continuum also associated with the active nucleus. Assuming that the 2–10 μm continuum in Seyfert 1s and 2s is AGN energy that has been re-radiated by dust grains (see 'Reprocessing' section below), even more unseen nonstellar power is implied in Seyfert 2s. This 'energy deficit' argues for a high-energy power source which is present but not directly observable. However, these arguments are not conclusive. The energy accounting has many large uncertainties, and there are other plausible explanations of the Kα emission line that do not require the existence of a buried AGN x-ray source. Although it is difficult to obtain the very sensitive observations required for these tests, many thorough observations have failed to reveal any direct evidence of nonstellar continuum from a central engine. The more extended indications which are seen in these Seyfert 2s—narrow emission lines and radio sources—could have been produced by an AGN which 'turned off' centuries ago.

This raises an empirical question of whether most Seyfert nuclei can turn on and off over intervals of centuries. Although none has been observed for that long[2], very few complete Seyfert 2 $\leftrightarrow$ Seyfert 1 transitions have ever been seen, in decades of observing. Nonetheless, the unification assumption is that all of these Seyfert 2s harbor a currently active central engine, which is just extremely obscured.

Even if unification is generally correct, it simply requires optically thick gas, with a very large associated dust extinction, between us and the nuclei of Seyfert 2 galaxies. All we know is that this obscuring region must be large enough to cover up the broad emission line region, as viewed by a significant portion of the lines of sight to the central engine[3]. Similarly, dust grains must intercept a substantial portion of the central continuum and reradiate it to produce the strong near- to mid-IR emission characteristic of both Seyfert 1 and 2 nuclei.

A popular special version of unification proposes that this absorbing matter is strongly nonspherical, and is distributed in a fat torus (of characteristic diameter parsecs to tens of parsecs) which is co-axial with the central engine. In the fat torus model the absence of obscuring material above the poles of the torus allows photons from the nuclear central engine to scatter into a clear line of sight to the Earth. The result would be a scattered nuclear spectrum—broad emission lines and nonstellar continuum—which we observe only in polarized light. Since the torus is supposed to be aligned with the axis of the central engine, the polarization E vector should be parallel to the radio axis. The latter is difficult to measure but is approximately parallel to the polarization in some of the best-measured Seyfert 2s. Further weak evidence for a preferred 'escape axis' for ionizing AGN photons is the loose tendency for extended ionized emission lines in Seyfert 2s to come from bipolar 'cones'.

In many Seyfert 2s, however, there is evidence (e.g. from HST imaging) that much obscuration instead occurs in galactic dust lanes. These are observed to be hundreds of parsecs in extent and not related to the central engine at all, except that they happen to block our view of it. It is still not clear how many, if any, Seyfert 1s and 2s really harbor complete fat tori wrapped around their central engines.

Thermal emission from an accretion flow

The enormous energy outputs from very small volumes that are observed in luminous quasars are believed to be generated by black hole accretion. To avoid greatly exceeding the Eddington limit, the accreting black holes must have masses of several 10^6–10^9 Suns. However, the conversion of the gravitational potential energy of the inflowing matter into radiation is not at all efficient if there is a purely radial infall. Also, general considerations of

[2] However, NGC 1068 = Messier 71 might, in a bright Seyfert 1 state, have been marginally visible to the naked eye.

[3] Since the space density of Seyfert 2s is somewhat higher than that of Seyfert 1s, this covering fraction of obscuration must be larger than 50%

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the angular momentum of gas deep in a galactic nucleus strongly suggest that the accretion flow must end up rotating rapidly as it nears the black hole. Then it can only accrete and power the AGN if it experiences friction. Although not yet well understood, this crucial process transfers angular momentum outward, allowing the black hole to be fueled. This accretion is accompanied by a large release of radiative energy, which powers the AGN. The fact that angular momentum is important in the accretion flow is supported by the observation that the central engine is bipolar. Its symmetry axis is naturally identified with the spin axis of the accretion flow and is the direction of the most likely outflows. There is also observational evidence that we observe directly the radiation emitted thermally from this accretion flow, as it spirals into the black hole.

One of the defining characteristics of the spectrum of the central AGN continuum source is a broad hump which appears to peak somewhere in the UV. This inflection, referred to as the 'ultraviolet excess' or 'big blue bump', often contains the largest portion of the total AGN luminosity.

The main arguments in favor of a thermal origin of this blue–UV continuum are as follows.

- *Its spectral shape*. The broad peak in the UV can be fitted by a sum of thermally emitting regions spanning a range of temperatures, centered on ~30 000 K. In a simple optically thick accretion disk, such as would be expected for most luminous AGN, the thermal temperature of the accretion flow is proportional to $r^{-3/4}$. With the inclusion of relativistic corrections, the sum of thermal emission from rings of varying radii adds up to a spectrum with a broad peak which is flat in flux density units (F_ν = constant) and has a high-frequency turn-over. Models which treat the disk as a sum of blackbodies provide remarkably good fits to all the optical–UV spectral energy distributions observed in AGN.
- *Its peak frequency*. The effective temperature in an accretion flow is approximately determined by the balance between the gravitational potential energy released as a result of viscous accretion and the radiation emitted[4]. In a thin disk this condition is $T_{\rm accretion} = (3GM_{\rm bh}\dot{M}/8\pi r^3)^{1/4} = (30\,000\,{\rm K})\,(M_8)^{1/4}(L/L_{\rm Eddington})^{1/2}$. The luminosities and peak frequencies observed in the continuum spectra of Seyfert 1 nuclei and quasars are consistent with the equilibrium temperatures predicted for disk accretion. The required respective mass infall rates are ~ several per cent and ~ tens of per cent of the Eddington limit for the inferred black hole masses[5].

Even for the highest plausible values of viscosity (corresponding to the most rapid inflow), the accretion flow is still expected to be very opaque to electron scattering and is probably effectively optically thick ($\tau_{\rm effective} = (\tau_{\rm es}\tau_{\rm ff})^{1/2} > 1$). The best observational evidence for this is the high inferred emissivity of the gas emitting the UV continuum. It is true that optically thin thermal models can also fit the observed optical–UV continuum. The characteristic temperatures of the bremstrahlung emission would have to be 100 000 K or higher, because free–free emission peaks at around $\nu_{\rm thin} = kT/h$, rather than the higher value for a Planck function: $\nu_{\rm thick} = 3kT/h$. EUV emission lines that might be expected from such a luminous plasma have not yet been seen. The most serious difficulty with the free–free hypothesis is explaining how the very large continuum luminosity of a quasar is emitted from a small area. For the UV brightness of a luminous quasar such as 3C 273 to vary on timescales of months requires a small thermally emitting region with high emissivity, so high, in fact, that the emitter must have an optical depth exceeding 1. At this point the emitted spectrum will resemble optically thick emission more than an optically thin $L_\nu \propto \exp(-h\nu/kT)$ spectrum.

The principal limitations or incompletenesses of the thin accretion disk model are the weakness of any observed spectral feature at the Lyman limit, the low amount of linear polarization, and multiwavelength monitoring evidence for reprocessing, discussed in the next section. The spectrum emerging from an accretion disk at a given radius depends on the vertical structure of the disk 'atmosphere'. A ring of an accretion disk differs radically from the atmosphere of any star, but it has recently become computationally feasible to make realistic non-LTE models of the emergent spectrum. Many UV-emitting rings of the disk have low enough temperatures that they should still contain some fraction of neutral hydrogen. This should lead to a sharp increase in the bound–free opacity across the Lyman edge. Some models predict that this will lead to a spectral jump, with the flux above the Lyman limit either higher or lower than the flux below it. These discontinuities are not in general observed. Opacity in the accretion disk is probably dominated by electron scattering. A pure electron scattering atmosphere of infinite optical depth viewed at an average inclination of $\cos i = 0.5$ should emit a thermal continuum which is linearly polarized by almost 3%. The position angle of the electric vector should be parallel to the projected major axis of the disk—perpendicular to the disk spin axis. However, observations show that most AGN polarizations are under 0.5% in the UV[6]. Also, in those cases where a radio 'axis' can be defined, it is not generally perpendicular to the E vector of the polarized flux. The greatest uncertainties in this test are the assumptions that the disk surface is perfectly flat and that magnetic fields in the disk are small enough to avoid causing appreciable Faraday rotation.

One deficiency of the simple thin accretion disk models that may be related to these observational conflicts

[4] In fact the viscous torques transport some of this potential energy outward, but most of it should eventually emerge as photons.

[5] Above the Eddington accretion rate, the disk is expected to thicken somewhat, but its overall observational properties may not change very greatly.

[6] However, the linear polarization appears, mysteriously, to increase dramatically, at rest wavelengths shorter than ~800 Å.

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is the likely presence of a hot optically thin corona above the photosphere of the disk surface. The fast electrons in this low-density gas can Comptonize the thermal photons escaping from the dense disk, modifying their spectrum and polarization.

Reprocessing

In the simplest accretion disk models, all of the thermal energy emitted by the disk was derived directly from gravitational potential energy, which is transported outwards by viscous torques. We know, however, that AGN also emit up to 10% or 20% of their luminosity at x-ray frequencies. These photon energies are too high to be readily explained by the thermal accretion disk paradigm, and their flux near the center is very high. Depending on the geometry, some of these x-rays could be re-absorbed by the optically thick accreting gas before they manage to escape. Some absorption of x-rays is probably required to explain the 'Compton reflection' hump observed around 10–30 keV (see discussion in ACTIVE GALAXIES: OBSERVATIONS). Reprocessing of x-rays is presumed to be the origin of the strong Fe Kα emission line seen in many AGN.

Reprocessing of photons at radii much larger than where they originated tends to degrade the energies of the photons that escape. In the simplest case, where the equilibrium blackbody temperature of the reprocessing matter drops as $T_{\rm equil} \propto L^{1/4}r^{-1/2}$ (where L is the luminosity of the central point source), the resulting thermal continuum spectrum tends to steepen to a slope of $L_\nu \propto \nu^{-1}$. Some reprocessing must occur; the main questions are: where and how much?

The first question is easy to answer assuming the absorbed photons are thermalized: the radius of the reprocessing determines $T_{\rm equil}$ of the emerging radiation, which should peak somewhere around a few $h\nu/kT_{\rm equil}$. The second question can be answered if we can measure the fraction of the total amount of energy which has been absorbed. If we assume that the reprocessing matter (gas, and dust if $T_{\rm equil}$ is under 1000 K) is opaque to incoming high-energy photons, then the energy budget can tell us its total sky covering fraction, i.e. the fraction of the sky as seen by the central continuum 'point source' which is covered by absorbers. By definition, the reprocessed luminosity cannot exceed the luminosity of the original high-energy continuum source in the center. It is actually unlikely that their luminosities would even be equal, because that would imply that 100% of the lines of sight to the center are blocked, in which case we should not be able to see it directly at all.

The best observational proof of reprocessing is to show that time variability in the primary waveband is then duplicated by the same flux changes at the reprocessed wavelength, except with a lag. The delay time in this 'reverberation' should equal the amount of time it takes light to travel across a region whose radius is given by the value of $T_{\rm equil}$ expected for the wavelength of the reprocessed continuum.

The best evidence for reprocessing is for the near-infrared continuum, which caries a substantial fraction (20% or more) of the total energy budget of most AGN. In several cases, simultaneous monitoring of the near-infrared and optical or UV continua has shown the expected correlated brightening and fading. The delay of the infrared light curve with respect to the light curve at shorter wavelengths is consistent with thermal re-emission by hot dust grains within a light year (or even light month) of the central powerhouse. The response is mostly from the hottest grains, surviving at just below their sublimation temperature of around 1000–1500 K. The distance from the central engine at which dust equilibrates to this temperature is proportional to the square root of the central luminosity, explaining the range of expected dust reverberation radii.

Less decisive evidence suggests that some of the optical continuum, and possibly even the UV continuum, in some Seyfert 1 nuclei, may have a measurable contribution from reprocessed x-rays. This is in several well-sampled x-ray and optical–UV light curves where a correlation and lag were detected. The lags are so small that they imply that the influence of the high-energy photons propagates outward to the low-energy emitting region at very high speed. The lags are consistent with this speed being c, as it should be if the influence is carried by photons which are then reprocessed. However, the variability of the x-rays (in other galaxies, as well as in some of these Seyfert 1s at other epochs) is often not correlated with changes at other wavelengths, casting doubt on whether much of the optical–UV light in most AGN is actually reprocessed from the x-rays.

Influence of host galaxies

Galaxies with Seyfert nuclei account for only a fraction of all galaxies. This estimation is complicated by the difficulty of identifying AGN with very low nonstellar luminosities. For example, many galaxies have weak emission line spectra with line ratios intermediate between those of H II regions and Seyfert nuclei, which are referred to as 'LINER' galaxies. Although these LINER spectra can be explained by fast shocks, they might still be included as having active nuclei (and the case is getting stronger for at least some of the members of this heterogeneous class). If so, then it is even possible that most galaxies are in some sense 'active'. The most definitive evidence of a truly nonstellar nucleus is probably a compact central source of hard x-rays, preferably variable. However, this would be obscured by gas with a column density of 10^{25} cm^{-2}, which is optically thick to Thomson electron scattering of hard x-rays. It may not be entirely surprising that, outside of the nucleus, the 'host galaxies' themselves hardly appear different from galaxies lacking obvious AGN. A very powerful AGN can have some limited effects on the interstellar medium of its galaxy, such as ionizing it, shocking and compressing it, and in some special cases even inducing stars to form, near an outflowing jet for example.

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A deeper mystery is what properties of the galaxy cause the AGN in the first place. The two most obvious ones are the origin of a massive black hole and the ability to provide enough fuel close into the nucleus to 'feed' it. The formation of a massive black hole probably requires the dynamical collapse of a dense star cluster in the dense center of a galaxy. As the first dense structures to come together in the young universe are thought to be proto-galactic bulges, there is some weak theoretical motivation for associating massive black holes with modern-day bulges. The dramatically higher (by orders of magnitude) proper space density of luminous AGN in the early universe requires that many seemingly 'normal' galaxies today must once have harbored an AGN central engine. If it was a black hole, it should still be present, and may be detectable by its gravitational acceleration of stars and gas within a few hundred parsecs. (The gravity of a black hole of mass M_{bh} dominates out to a radius of roughly GM_{bh}/σ^2 where σ is the characteristic velocity dispersion in the stellar system.) This region is small enough that it can only be resolved optically in the nearest galaxies with the best spectrographs (Hubble Space Telescope, or ground-based telescopes with excellent seeing). The kinematic search for nearby massive black holes (using Doppler spectroscopy to measure orbital velocities around the nucleus) is still in its early phases, with less than a few dozen detections (see also SUPERMASSIVE BLACK HOLES IN AGN). These provide a tentative suggestion that the central black hole mass might correlate linearly with the total galactic bulge mass, with a normalization constant of about half of a per cent. However, this claimed correlation may have enormous scatter or may not even prove significant when an unbiased sample of galaxies is studied intensively and upper limits to M_{bh} are all included.

In the near future, the set of galaxies with reliable central black hole masses has unfortunately very little intersection with the set of active nuclei for which mass estimates can be attempted. This is because the latter is measured from nonstellar emission, while the former comes from nonactive emission. If one of these dominates and is easily studied, the other will not be well measured. Nonetheless, the current evidence on black holes, mostly in nonactive galaxies, suggests that the key potential ingredient for the central engine—the massive black hole—may be present in many or even most galaxies. The fact that most of them today are not Seyferts must then be attributable to a lack of fuel.

Even assuming the most efficient known models, black hole accretion disks, the energetics of the most powerful quasars require tens of solar masses per year to be supplied to the central parsec of the galaxy. To reach such a small radius, the fuel—probably gas—must lose essentially all of its orbital angular momentum. On theoretical grounds, the required torques may be provided by distortions and asymmetries in the gravitational potential of the host galaxy, such as bars (see GALAXIES: CLASSIFICATION; FORMATION)[7].

Unfortunately, it has been difficult to show much association between the presence of close companions and an active nucleus. Also there is no correlation between bars and Seyfert activity. One possibility is that bars and/or encounters only enhance nuclear activity with a great delay (of perhaps a billion years), since it could take that many orbits for the gas to eventually fall down into the nucleus. One possible indication of this is the finding that Seyfert galaxies are more likely to show rings, which may be long-lived relics of bars that have already dissipated. A possible connection between Seyfert activity and earlier star-formation activity is the observation that the disks of Seyfert host galaxies tend to have higher surface brightnesses than those of non-Seyfert galaxies.

Future prospects

Understanding AGN is a seriously data-limited problem. Its typical variability proves that the central engine is not in a steady state. We can turn this into an asset in trying to understand it, but only if we can obtain extensive, nearly continuous time histories of the emission from individual AGN. Beyond limited time sampling, the two most serious observational limitations have been the following.

- *Inadequate observations of many of the wavelength regions where AGN emit*. AGN are the most broad-band emitters in the universe, and many of the wavelengths at which they emit are blocked by the Earth's atmosphere, or more fundamentally by H I absorption in the intergalactic medium (shortward of a rest wavelength of 912 Å).
- *Inadequate spatial resolution*. The largest relevant scales for most of the interesting and extreme AGN phenomena are of order 10 pc or even less.

Fortunately both of these limitations are rapidly easing with the advent of new detectors and observatories. The critical AGN observations during the next decade will benefit from new and planned space observatories and new ground-based techniques such as interferometry. Also, the ultimate in spatial resolution is becoming available by using intensive monitoring to detect light-travel delays, as in reverberation mapping.

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[7] Two controversial observational claims may support applying this idea to star formation. One is that spiral galaxies with bars are more likely to have higher rates of recent star formation than unbarred spirals. Another is that close galaxy encounters, which also apply an $n = 2$ mode perturbation to the galactic potential, are also associated with elevated rates of star formation.

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