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On the History and Present Situation

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Abstract. A common thought in the 1950s was that galaxies rotate because they are remnants of primeval currents, as in turbulence. But this idea is quite unacceptable in an expanding universe described by general relativity theory. Since we are no smarter now than in the 1950s the lesson I draw is that we do well on occasion to pause to consider whether we might be missing something. An example is the pure disk galaxies that are so common nearby and so rare in simulations. We have something to learn from this.

Keywords. galaxies: bulges, galaxies: formation, cosmology: theory.

Carl Friedrich von Weizsäcker (1951) argued for the likely importance of turbulence in protoplanetary disks, and he proposed that turbulence may also play a role in galaxy formation: "I do not propose a theory of the origin of this initial turbulence" but "it is a consistent theory to think of the galaxies (or perhaps the clusters of galaxies) as the largest eddies of a cosmic turbulence that existed a couple of billion years ago." Von Weizsäcker's student Sebastian von Hoerner had a distinguished career in radio astronomy and SETI. In a paper while still at the University of Gottingen, von Hoerner (1953) considered how matter might be distributed in a galaxy that grew out of a turbulent eddy. He concluded that (in my translation) "Since we have obtained qualitatively consistent statements on the surface density run in spiral nebulae in three completely different ways, we will consider this result as an argument for the applicability of the assumed turbulence theory."

George Gamow was an intuitive genius but not always careful with details. He felt the present mean mass density is far too low for the gravitational assembly of galaxies. He and Teller had proposed that this meant galaxies formed at high redshift, when the density would have been more important. But Gamow (1954) argued that "The only escape from this difficulty is to assume the existence of very large original density fluctuations in the primordial gas ... in a turbulent state. Besides, in order to permit large variations of density, this turbulence must have been supersonic." Gamow's student Vera Rubin had a distinguished career in astronomy, with particular attention to the informative role of rotation curves of galaxies. In her PhD thesis she introduced and applied statistical measures of the galaxy distribution; she pioneered an important line of research. Rubin (1954) concluded that her statistical measures are "physically reasonable if the galaxies have condensed from a turbulent gaseous medium."

The relation between student and teacher can be complicated. We can only wonder how enthusiastic these two students were about their evidence for primeval turbulence.

In an important review Jan Henrik Oort (1958) showed that the empirical support for cosmology was scant but by no means trivial. Oort argued that "Most galaxies deviate greatly from the spherical shape and have a considerable angular momentum. The total angular momentum must have been present in the primeval clump of material from which the galaxy has contracted." Turbulence is not mentioned, but I count Oort's picture as a variant of the concept of primeval currents.

Leonid Ozernoi was a leading figure in exploration of the primeval turbulence picture in the early 1970s. We agreed that primeval turbulence calls for irrotational flow, $\bigtriangledown \times \vec{v} = 0$. This is because currents with nonzero divergence would produce density fluctuations that (with a reasonable mass density) would grow by gravitational attraction, the usual gravitational instability picture. Suppose the primeval irrotational flow has comoving coherence length y, or physical length $a(t)y$ at expansion time t, where $a(t)$ is the expansion parameter. How the flow behaves depends on the ratio

$$R(t) = \frac{v(t)t}{a(t)v}, \text{ where } R(t) \propto a(t) \text{ if } p = p/3, \; R(t) \propto a(t)^{-1/2} \, ifp = 0. \tag{1}$$

At redshift $z > z_{\rm eq} = 5000$ the universe was dominated by radiation and $R(t)$ would have been growing. If $R(t)$ approached unity flows moving in different directions would have encountered each other and been forced to change direction. That is, turbulence would have formed and decayed to viscosity. But this is far too early for galaxy formation. At $z < z_{\rm eq}$ the ratio $R(t)$ decreases, so if turbulence had not developed by then it would not develop. I concluded (Peebles 1971a) that the primeval turbulence theory is not viable. Ozernoi (1972) disagreed (by long distance, he was in the USSR). Interest in primeval turbulence continued through the 1970s, but attention was turning to the role of gravity.

At the conference where von Weizsäcker (1951) spoke about primeval turbulence Fred Hoyle (1951) proposed that gravitational transfer of angular momentum caused galaxies to rotate. He evidently was unaware that Gustaf Strömberg (1934) had expressed similar thoughts some two decades earlier. (I am grateful to Matthias Steinmetz for alerting me to Strömberg directly after my IAU lecture.) As Hoyle put it, a young protogalaxy would have been an irregular blob that could be torqued by the gravitational field gradients of neighboring blobs, transferring angular momentum. His estimate of the effect suggested this is a credible explanation of why galaxies rotate.

The NASA archive ADS lists no citations to Hoyle's paper for the next two decades, and no citations to Gustaf Strömberg (1934) until 1995. The rate of research in cosmology through most of the 20th century was modest. Another example is the exchange with Werner Heisenberg after Hoyle's talk:

Heisenberg: "How can an irregular thing like a cloud have originated otherwise than as a consequence of turbulent motion?"

Hoyle: "A cloud can form in a more or less uniform medium through gravitational instability."

Heisenberg: "This possibility exists, but wouldn't you say that if we believe in the expanding universe (I know that some of us do not but that is another matter), then we should also assume that there is an enormous energy in this primary cosmic gas which expands? Now, if there is this enormous kinetic energy of the gaseous masses, I suppose there must be turbulence, because the turbulent motion is the normal motion of the gas, whereas laminar flow is extremely exceptional."

In the late 1960s I was taken by the idea that galaxies, and their clumpy spatial distribution, grew by the gravitational instability of the expanding universe. I had to explain why galaxies rotate. I did not know Hoyle's 1951 argument then, but worked along similar lines in my computation of the gravitational angular momentum transfer. The analytic estimate in Peebles (1969) amounts to

$$\lambda \equiv \frac{L|E|^{1/2}}{GM^{5/2}} \sim 0.08. \tag{2}$$

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Here L is the angular momentum of the newly assembled protogalaxy, M is its mass, and E is its gravitational binding energy. (This combines eqs. [35] and [36] in Peebles 1969. I introduced λ in Peebles 1971b).

Oort (1970) argued that I had seriously overestimated the gravitational transfer of angular momentum, and concluded that galaxies "must have been endowed with their angular momentum from the beginning." That led me to compute the angular momentum transfer in numerical N-body simulations. They indicated $\lambda = 0.07^{0+1}_{0.03}$. These simulations had $N = 90$ to 150 particles. This is ludicrous by today's standard, but that was a different age. In this paper I ventured to add that since λ is a pure number set by the scale-invariant physics of gravity and a pressureless ideal gas one might expect λ to be of order unity. What other value might it have?

I don't know which of my arguments was the more persuasive, but after publication of this paper Oort sought me out to explain, not at length but quite clearly, that he withdrew his objection to my result. It was an edifying example for this callow youth.

Efstathiou and Jones (1979) found $\lambda = 0.07 \pm 0.03$ in simulations with $N = 1000$ particles. That number also is tiny by today's standards, but far better than I did, and I suppose large enough to make the case: gravity in an expanding Einstein-de Sitter universe produces angular momentum in the neighborhood of $\lambda \sim 0.1$

The next advance was the proposal, independently by White and Rees (1978) and Gunn, Lee, Lerche, *et al.* (1978), that the luminous parts of galaxies formed by dissipative settling of baryonic gas and plasma in subluminal massive halos. (Gunn *et al.* had in mind halos of nonbaryonic matter, later known as WIMPS. White and Rees felt that remnants of early stellar generations are more likely forms of subluminal matter, but that nonbaryonic dark matter would do.) Neither paper mentions rotation of galaxies.

Gustaf Strömberg (1934) and Fall (1979) pointed out that dissipative settling could spin up a young galaxy. Fall could be more explicit: it could bring $\lambda \sim 0.1$ up to the value $\lambda \sim 1$ suitable for the disk of a spiral galaxy. Fall and Efstathiou (1980) elaborated on this point. Let v_c be the speed of rotation of a newly gravitationally assembled protogalaxy, and let $\mathrm{v}_r \sim (GM/R)^{1/2}$ be its internal speed of support, mainly random. The angular momentum parameter is, roughly, $\lambda \sim v_c/v_r$. Suppose that after assembly the bulk of the mass dissipatively settled by the factor α. The rotation speed would scale up as $v_c \propto \alpha$, and the speed of pressure support would increase as $v_r \propto \alpha^{1/2}$. So we see that the protogalaxy would have to have collapsed by a factor $\alpha \sim \lambda^{-2} \sim 100$ to get to rotational support. That seems excessive. Surely the protogalaxy would instead fragment into something like an elliptical galaxy. But if instead the diffuse baryons settled in a subluminal massive halo with density run $\rho \propto r^{-2}$, and the diffuse baryon mass were subdominant, then spin-up would require settling by the factor $\alpha \sim \lambda^{-1} \sim 10$. This factor of ten is about what Eggen, Lynden-Bell, and Sandage (1962) found could account for the metal-poor high-velocity stars in the Milky Way. It's a valuable sanity check.

By 1980 gravitational transfer of angular momentum had become the standard and accepted explanation of why galaxies rotate. That was followed by the development of increasingly detailed numerical simulations of how baryons and dark matter gather by gravity and non-gravitational stresses in all their complexities to produce what are now impressively good approximations to real galaxies. I don't imagine much attention is given to λ anymore; the simulations take care of it.

If primeval turbulence is so manifestly wrong, as I argue, why was the idea so commonly accepted in the 1950s and 1960s? There was phenomenology: spiral galaxies call to mind turbulent eddies. The expanding universe was familiar, but not so carefully considered, or so well trusted, as to make the idea of primeval turbulence seem suspicious. Recall Heisenberg's remarks. And we must bear in mind that ideas can be self-reenforcing: people analyzed primeval turbulence because others had.

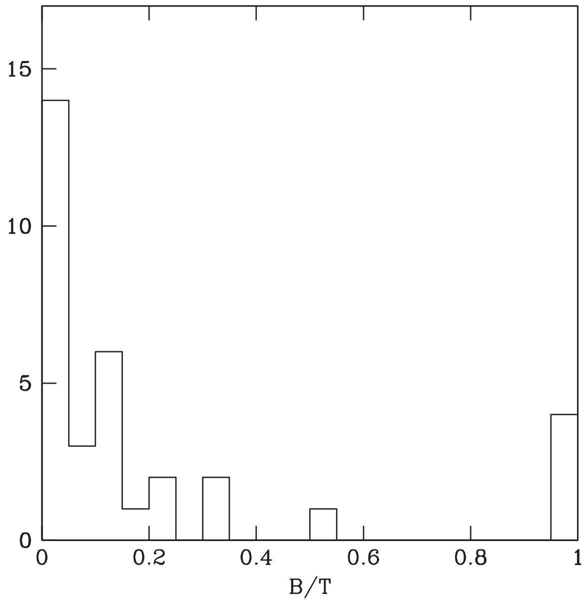

Figure 1. Distribution of bulge to total luminosities of the largest galaxies within 10 Mpc.

I began with the thought of pausing on occasion to consider whether, as for primeval turbulence, we are overlooking something. I offer the paper by Kormendy, Drory, Bender, and Cornell (2010), with the title *Bulgeless Giant Galaxies Challenge Our Picture of Galaxy Formation by Hierarchical Clustering.* I suggest that those who do not often admire the wonderfully detailed images of nearby galaxies to be seen on the web contemplate NGC 1300. (The reader is referred to the high-resolution HST image.) I don't see a classical bulge; the central region looks like a whirlpool. Would an HST image reveal its funnel? or maybe a star cluster? Also worth contemplating is the image of M 101 in Figure 3 in Peebles (2014), adapted from Kormendy *et al.* (2010). It has a central star cluster with luminosity about a part in 10^5 of the galaxy. The galaxy spiral arms are seen all the way in to this relatively tiny star cluster. I suppose gravity in the disk produces the spiral arms, and so expect that the central part of this galaxy cannot be dominated by mass in a classical stellar bulge.†

The variants of the pure disk phenomenon seen in NGC 1300 and M 101 seem to be common among the nearest large galaxies that can be examined in closest detail. Brent Tully's Local Universe catalog‡ lists 38 galaxies closer than 10 Mpc with K-band luminosity greater than 10^{10}. (I can't find K-band luminosities for a few, but they have large optical luminosities.) The fractions B/T of galaxy luminosities that are in classical bulges are given by Kormendy Kormendy *et al.* (2010) and Fisher and Drory (2011) for 33 of these 38 galaxies. Figure 1 shows the distribution. Three ellipticals are at the far right. Near the center is the Sombrero Galaxy, also well worth a visit to the web. The

† I might state my understanding that a classical bulge is supported by near isotropic stellar velocities that cause the stars to move in a near axisymmetric distribution that may rise above the disk. Stars rise above the disk in the peanut-shaped bar in the Milky Way, but I suppose this would not be termed a classical bulge. I am cautioned that a bulge luminosity derived from the excess above a pure exponental fit to the surface brightness run may be in a classical bulge, or it may be a departure from an exponential distribution of the stars moving in the disk.

‡ Available at the Extragalactic Distance Database, `http://edd.ifa.hawaii.edu`, as the catalog "Local Universe (LU)"

galaxies M 31 and M 81 are next to the left of center. The rest of these large galaxies are still further to the left, most judged to have little or no light in classical bulges.

My impression is that distributions of B/T in recent large-scale simulations peak at B/T close to 50%, quite unlike Figure 1. This is not a criticism: the authors are reporting results from painstakingly careful work. I have not detected much concern in the galaxy formation community about the failure to match Figure 1. This is sensible: galaxy model building has encountered and resolved many other problems; maybe this is just one more. But I offer the cautionary reminder of earlier thinking about primeval turbulence. We are much better informed now, but we are reaching much further, on still quite modest empirical grounds. Star formation is observed in some detail, but it still must be schematically modeled in galaxy formation simulations. Dark matter and Einstein's cosmological constant are not even observed, apart from their gravitational effect. So although the ΛCDM theory passes demanding tests it may need improving. Thinking in cosmology has been redirected, sometimes by closer consultation of the theory, as for primeval turbulence, sometimes by observation, as in the falsification of the 1948 steady state cosmology. You can think of other examples. The pure disk phenomenon is a case of déjà vu all over again; it is certain to teach us something of value. That may be about how pure disks can be understood within the present paradigm. Or it may serve to redirect our thinking once again, toward a still better cosmology.

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