Galaxy formation catalyzed by leaky “black” holes, and the JWST

Stephen L. Adler

Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA.

We have proposed that galaxy formation is catalyzed by the collision of infalling and outstreaming particles from leaky, horizonless “black” holes. This gives an estimate of the local ($z \sim 0$) disk galaxy scale length as $\ell \sim (\pi a_0^2 \rho_H)^{-1} \simeq 3.2$ kpc, where $a_0$ is the Bohr radius and $\rho_H \sim 1m^{-3}$ is the density of atomic hydrogen in the proto-galactic region. This formula is in good agreement with observation, and suggests that the scale size of galaxies is fundamentally a property of atomic hydrogen. In the early universe at redshift $z \simeq 11$, this formula predicts a very small disk galaxy scale length of $3200/(12^3) \sim 2$ pc, which corresponds to galaxies seen as single pixels in the James Webb Space Telescope. With this prediction in mind, we suggest a possible method for estimating the diameter of sub-pixel sized galaxies by observing their transit between adjacent pixels.

I. WHAT LIES INSIDE THE LIGHT SPHERE?

The Event Horizon Telescope (EHT) \cite{EHT} has established, by viewing Sgr A* in our galaxy, and M87* in a neighboring galaxy, that for a black hole of mass $M$, the minimal stable orbit for photons, called the “light sphere”, lies at the radius $3M$. So the compact objects viewed by the EHT have the expected exterior geometry of a mathematical black hole. But because of the Birkhoff uniqueness theorem \cite{Birkhoff} for spherically symmetric solutions of the Einstein equations, the object interior to radius $M$, whether a true black hole or an exotic compact object (ECO) \cite{ECO} mimicking a black hole, will have to high accuracy the same exterior geometry. Thus a key experimental question remains: What type of object lies inside the observed light sphere?

Two approaches have been suggested to attempt to resolve this question. The first, reviewed in \cite{ECO}, uses as a diagnostic the ringdown gravitational waves emitted in mergers of two holes. The form of the waves emitted will have a different structure if the holes are true mathematical black holes with an event horizon, as opposed to the case in which the holes are ECO’s. A second approach \cite{leaky} notes that if “black”\footnote{Since leaky holes will not be exactly black, in this context we put black in quotes.} holes have no event horizon or apparent horizon, then they will be “leaky”, and interior particles will be able to exit. This can influence astrophysical processes, such as young

*Electronic address: adler@ias.edu
star formation near the object Sgr A* central to our galaxy [5], and galaxy formation itself [6], as discussed now in more detail.

II. LEAKY “BLACK” HOLES AS CATALYSTS FOR GALAXY FORMATION

In a recent Gravitation Essay [6], we have proposed that horizonless “black” holes can act as the catalysts for galaxy formation. This suggestion was originally motivated by a novel model for dark energy (reviewed in [7]) that suppresses formation of black hole event horizons [8] and apparent horizons [4], suggesting that black holes may be leaky [4]. More recently, we have studied [9] a modification of Mazur-Mottola gravastars [10] (which are an examplar of ECO’s [3]). Our modified version is based on using the Tolman-Oppenheimer-Volkoff equation [11], in which the pressure is continuous, and the jump to a Gliner [12] ground state with pressure plus density summing to near zero is through a jump in the energy density. We found that even in the absence of a cosmological constant, this model gives a gravastar “black” hole with a metric that joins smoothly to an exterior Schwarzschild solution. The metric component $g_{00}$ in the gravastar is always positive, and takes small to very small values in the interior. In such a gravastar, there is a very small black hole leakage or “wind” driven by the cosmological constant, but a much larger black hole wind can arise from accreting particles which exit the hole, on a time scale that depends on their impact parameter relative to the center of the hole. This gives a concrete model in which the black hole catalysis mechanism of [6] can be realized, while simultaneously allowing hole growth along with growth of the galaxy.

A peculiar feature of galaxies is the existence of a diffuse structure that unfolds over many decades of length scales. The model of [6] ties this to the recent observation that nearly all galaxies have massive black holes at their center, by suggesting that “black” holes seed the formation of stars that constitute the galaxy, through collisions of outstreaming with infalling particles. A simple calculation of radial geodesic motion shows that at any distance from the central hole, the outstreaming and infalling particle velocities are identical, and so the center of mass of the collision has no radial motion, permitting nucleation of star formation over a wide range of length scales from the central hole. If $\ell$ is the collision length of the outgoing particles (taken as neutral hydrogen), then the number of outstreaming particles at any radius from the central hole scales as $\exp(-r/\ell)$, corresponding to an exponential scale length structure as observed for nearly all disk galaxies. A geometric estimate of the collision length is $\ell \simeq (A_H \rho_H)^{-1}$, where $A_H = \pi a_0^2$ is the cross sectional area of a hydrogen atom, giving the formula for the scale length quoted above in
the Abstract. Initially this mechanism will give rise to spherical galaxies, which then relax into disks through dissipation with conservation of angular momentum.

III. IMPLICATIONS OF THIS MECHANISM FOR JWST OBSERVATIONS

The mechanism of [6] has a striking implication for observations of high redshift galaxies by the James Webb Space Telescope (JWST). Since the density of hydrogen in the early universe scales with redshift $z$ as $\rho_H(z) = \rho_H(z = 0)(1 + z)^3$, the scale length of galaxies should scale correspondingly with $z$. For example, at a redshift of $z = 11$, the scale length will be reduced by a factor $12^3 = 1728$, so the scale length at $z = 11$ will be of the order a few parsecs rather than a few kiloparsecs as observed locally. Two galaxies reported from JWST measurements by Naidu and Oesch et al. [14] at $z = 11$ and $z = 13$ are much larger than this, with scale lengths estimated as 0.7 kpc and 0.5 kpc respectively. If these are generic early universe galaxies they falsify our model, but they may also be outliers in a distribution over several decades of galaxy sizes, chosen for initial analyses precisely because they are more visible. If this is the case, one expects the presence of larger numbers of smaller galaxies. From Fig. 4 of [14], which shows 1 kpc on the residual pixel map, one sees that 1 kpc corresponds to roughly 7 pixels, so the pixel size at $z = 11$ is roughly 0.14 kpc. Thus, a galaxy with a 2 pc scale length would fit entirely within one pixel. Hence the prediction of our galaxy formation model [6] is that the JWST sky maps should contain large numbers of single pixel galaxies!

IV. POSSIBLE WAY TO ESTIMATE THE DIAMETER OF SUB-PIXEL BRIGHT GALAXIES

This prediction raises the question of whether one can estimate the size of galaxies that are contained within a single pixel of an image. This may be possible by slowly shifting the camera charge coupled device at a rate that corresponds to a motion in the observed image of $v = dL/dt$. If a single pixel galaxy moves off the edge of the pixel, and the elapsed time from when the observed intensity starts to decrease until it is zero is $\Delta t$, then to within factors of order unity the actual dimension of the galaxy can be estimated as $\Delta L \sim v\Delta t$. When the galaxy appears in an adjacent

---

2 Other mechanisms have been suggested for producing an exponential disk density profile, although without fixing the magnitude of the scale length $\ell$. A mechanism based on maximizing entropy under angular momentum mixing by radial migration has been suggested by Herpich, Tremaine, and Rix [13], and they give extensive references to earlier proposals. Their mechanism suggests that an initially formed exponential density profile, as in our proposal, would be stable under subsequent galactic dynamics.
pixel (after a delay if there is a dead zone between pixels) the time for the observed intensity to ramp up will give a similar estimate. We note that if galaxies in the $z = 11$ universe are spaced at the current intergalactic spacing of $\sim 300,000$ pc rescaled by $z = 11$, that is spaced by $30,000$ pc or $30$ kpc, then a single pixel of extent $0.14$ kpc is unlikely to contain more than one galaxy. So the shift mechanism that we are suggesting will not have to deal with the presence of multiple galaxies in a single pixel.

V. SUMMARY

We have discussed how the nature of the structure lying interior to the light sphere observed by the EHT, relates to issues of “black” hole leakiness, a “black” hole catalysis mechanism for galaxy formation, a formula for the disk galaxy scale length, and early universe galaxy pixel spans observed in the JWST.

[1] Event Horizon Telescope, Phys. Rev. Lett. 125, 141104 (2020), arXiv:2010.01055.
[2] https://en.wikipedia.org/wiki/Birkhoff
[3] V. Cardoso and P. Pani, Living Rev. Relativ. 22: 4 (2019), arXiv:1904.05363.
[4] S. L. Adler, Int. J. Mod. Phys. D 31, 2250070 (2022), arXiv:2107.11816.
[5] S. L. Adler and K. Singh, “A One-Dimensional Model for Star Formation Near a ‘Leaky’ Black Hole”, arXiv:2112.12319.
[6] S. L. Adler, “A mechanism for a ‘leaky’ black hole to catalyze galaxy formation”, Int. J. Mod. Phys. D (in press), arXiv:gr-qc/2112.12491.
[7] S. L. Adler, Modern Physics Letters A 36, 2130027 (2021), arXiv:2111.12576.
[8] S. L. Adler and F. M. Ramazanoğlu, Int. J. Mod. Phys. D 24, 1550011 (2015), arXiv:1308.1448.
[9] S. L. Adler, “Dynamical Gravastars”, Phys. Rev. D (in press), arXiv:2209.02537.
[10] P. O. Mazur and E. Mottola, “Gravitational Condensate Stars: An Alternative to Black Holes”, arXiv:gr-qc/0109035 (2001). See also Proc. Nat. Acad. Sci. 101, 9545 (2004), arXiv:gr-qc/0407075.
[11] Ya. B. Zeldovich and I. D. Novikov, Stars and Relativity, The University of Chicago Press (1971, pp. 256-257, gives a succinct derivation and references.
[12] E. B. Gliner, J. Exptl. Theoret. Phys. 49, 542 (1965); translation in Sov. Phys. JETP 22, 378 (1966).
[13] J. Herpich, S. Tremaine, and H.-W. Rix, MNRAS 467, 5022 (2017), arXiv:1612.03171.
[14] R. P. Naidu, P. A. Oesch et al., arXiv:2207.09434.