SIX NOVEL OBSERVATIONAL TESTS OF GENERAL RELATIVITY

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ABSTRACT

I study six novel observational tests of general relativity. First, I show that a gravitational wave pulse from a major merger of massive black holes at the Galactic center induces a permanent increase in the Earth-Moon separation. For black holes of mass $\sim 10^6 M_\odot$, the shift in the local gravitational potential is comparable to the Earth-Moon potential, leading to the Moon being perturbed relative to the Earth during the passage of the pulse. The permanent increase in the Earth-Moon separation is a fraction of a millimeter, measurable by lunar ranging for future merger events. Second, I show that General Relativity sets an absolute upper limit on the energy flux observed from a cosmological source as a function of its redshift. Detecting a brighter source in gravitational waves, neutrinos or light, would flag new physics. The derived flux limit can also be used to determine the maximum redshift possible for any source with an unknown origin. Third, I consider the implications of modified inertia at low accelerations for rockets. An attractive interpretation of MOfied Newtonian Dynamics (MOND) as an alternative to dark matter, changes the inertia of matter at accelerations $a \lesssim a_0 \approx 1.2 \times 10^{-8}$ cm s$^{-2}$. I show that if inertia is modified at low accelerations, this suppresses the exponential factor for the required fuel mass in low acceleration journeys. Rockets operating at $a \ll a_0$ might allow intergalactic travel with a modest fuel-to-payload mass ratio. Fourth, I show that in MOND the amplitude of the observed dipole of the Cosmic Microwave Background (CMB) can originate from the primordial fluctuation amplitude on the scale of the cosmic horizon. Fifth, I show that the tidal gravitational potential of the Milky-Way galaxy removes fuzzy dark matter from its satellite dwarf galaxies through quantum-mechanical tunneling. The existence of dark matter in satellites rules-out ultra-light axions (ULAs) as dark matter with a particle mass, $m_a < 2 \times 10^{-21}$ eV. This limit exceeds the canonical mass range proposed as a solution to the small-scale challenges of the cold-dark-matter paradigm. Sixth, I show that a charged particle can be accelerated to arbitrarily high energies by maintaining a permanent resonance with the phase of a planar gravitational wave propagating along a uniform magnetic field. The
Doppler-shifted cyclotron autoresonance could potentially result in electromagnetic afterglows near gravitational-wave sources.
1. DETECTING THE MEMORY EFFECT FROM A MASSIVE BLACK HOLE MERGER AT THE GALACTIC CENTER THROUGH LUNAR RANGING

The black hole at the Galactic Center, SgrA*, grows in part through mergers of black holes of mass $M_{BH} \sim 10^6 M_\odot$ (Micic et al. 2011; Greene et al. 2020). Here we calculate the imprint of such mergers on the Earth-Moon separation.

A merger between black holes of the above mass results in a gravitational wave pulse of a characteristic duration,

$$ (\Delta t)_{GW} \sim \left( \frac{GM_{BH}}{c^3} \right) \sim 5 \text{ s}. \quad (1) $$

The mass equivalent of the radiated energy, $(\Delta M)_{GW}$, changes the near-Earth gravitational potential by an amount,

$$ (\Delta \phi)_{GW} \sim \frac{G(\Delta M)_{GW}}{d_{GC}} = 0.6 \times 10^{-11} c^2 \left[ \frac{(\Delta M)_{GW}}{M_{BH}} \right], \quad (2) $$

where $c$ is the speed-of-light, $d_{GC} \approx 8 \text{ kpc}$ is the distance of the Galactic center from the Sun (Reid et al. 2019), and typically $(\Delta M)_{GW} \lesssim 0.1 M_{BH}$ (Healy et al. 2014).

Coincidentally, this shift in gravitational potential as a result of the energy carried by the pulse happens to be comparable to the gravitational potential that binds the Moon to Earth,

$$ \phi_\oplus = \frac{GM_\oplus}{d_\text{Moon}} = 10^{-11} c^2, \quad (3) $$

where $M_\oplus = 6 \times 10^{27} \text{ g}$ is the mass of the Earth and $d_\text{Moon} \approx 4 \times 10^{10} \text{ cm}$ is the Earth-Moon distance.

The gravitational radiation pulse traverses the Earth-Moon system over a light-crossing time $(\Delta t)_{\text{cross}} \sim (d_\text{Moon}/c) \sim 1.3 \text{ s}$, during which the gravitational-potential change affects one of the objects before the other. For $(\Delta \phi)_{GW} \lesssim \phi_\oplus$, the temporary weakening of the gravitational binding between the Earth and the Moon during the passage period $(\Delta t)_{\text{cross}}$ leads to an increase in the Earth-Moon separation by an amount,

$$ \left( \frac{\Delta d_\text{Moon}}{d_\text{Moon}} \right) \sim \left( \frac{(\Delta \phi)_{GW}}{\phi_\oplus} \right) \times \frac{1}{2} \left( \frac{v_\text{Moon}(t)_{\text{cross}}}{d_\text{Moon}} \right)^2 \sim 0.3 \times 10^{-11} \left[ \frac{(\Delta M)_{GW}}{M_{BH}} \right], \quad (4) $$

where $v_\text{Moon} \approx 1 \text{ km s}^{-1}$ is the Moon’s orbital speed, and the geometric calculation ignored the small eccentricity in the Moon’s orbit.

The above increase in distance as a result of the motion of the Moon relative to Earth is of the same magnitude as the known “memory effect” (Zel’dovich & Polnarev 1974; Braginskii & Grishchuk 1985; Christodoulou 1991; Bieri et al. 2012), for which the permanent change in separation between free-floating objects of negligible mass initially at rest relative to each other, is also of order, $(\Delta d_\text{Moon}/d_\text{Moon}) \sim [(\Delta \phi)_{GW}/c^2]$.
The resulting permanent change $\Delta d_{\text{Moon}} \sim 1 \text{ mm}[(\Delta M_{\text{GW}}/M_{\text{BH}}) \sim 10^{-14}$, and could be measured for future merger events.

A tight binary of black holes with individual masses $\sim 2 \times 10^6 M_{\odot}$ and a separation $a$ would merge on a timescale of $\sim 40 \text{ yr}$ ($a/10^{14} \text{ cm}$) (Peters 1964). The existence of such a binary is not ruled out by the orbits of the S-stars which are observed at much larger distances, $\gtrsim 10^{15} \text{ cm}$ (Gualandris et al. 2010).

The permanent displacement from the memory effect would increase slightly the eccentricity of stellar binaries at wide separations $\gtrsim 10^{16} \text{ cm}$, but this imprint is not detectable at the precision enabled by astronomical surveys such as Gaia (Hwang et al. 2022), even when considering the increase in its amplitude with decreasing Galactocentric distance.

2. LIMITING FLUX VERSUS REDSHIFT AS A FLAG OF NEW PHYSICS

According to General Relativity, the maximum possible luminosity of a source which is bound by its own gravity, equal to its total rest-mass energy, $M c^2$, divided by the light crossing-time of its gravitational radius, $G M/c^2$. This limit applies to all possible carriers of energy, including gravitational waves, elementary particles such as neutrinos, or electromagnetic radiation. Packing the energy to a smaller scale would result in an implosion to a black hole according to the hoop conjecture (Peng 2021), and a shorter emission time would require faster than light travel (Schiller 2021; Jowsey & Visser 2021; Cardoso et al. 2018; Hogan 1999). These considerations are purely classical and do not involve quantum mechanics.

The ratio between the maximum emission energy and the minimum emission time is independent of mass $M$, implying that the maximum luminosity is a universal constant, combining the speed of light $c$ and Newton’s constant $G$,

$$L_{\text{max}} = \frac{c^5}{G} = 3.64 \times 10^{59} \text{ erg s}^{-1}. \quad (5)$$

A similar argument can be applied to any self-gravitating system of size $r$, where the characteristic velocity $v$ is dictated by the virial theorem, $v^2 \sim G M/r$, and the characteristic energy release time is limited by the crossing-time, $\sim r/v$, so that the limiting output power is $\sim v^5/G$, smaller by a factor of $\sim (v/c)^5$ than the universal limit in equation (5).

Given the luminosity distance as a function of redshift, $d_L(z)$, the above limit gives a maximum energy flux that can be observed from a cosmological source which emits isotropically any form of radiation or relativistic particles,

$$f_{\text{max}}(z) = \frac{L_{\text{max}}}{4\pi d_L^2(z)}. \quad (6)$$

To quantify this universal flux limit, I use an analytic approximation to $d_L(z)$ which is accurate to a sub-percent level (Adachi & Kasai 2012) for the standard flat
cosmology with a matter density parameter $\Omega_m = 0.32$ and a Hubble constant of 70 km s$^{-1}$ Mpc$^{-1}$ (Planck Collaboration et al. 2020). This gives,

$$f_{\text{max}}(z) = \frac{13.26 \text{ erg s}^{-1} \text{ cm}^{-2}}{(1 + z)^2 \{\phi(2.13) - (1 + z)^{-1/2}\phi[2.13(1 + z)^{-3}]\}^2},$$  \hspace{1cm} (7)$$

where,

$$\phi(x) \equiv \frac{1 + 1.32x + 0.4415x^2 + 0.02656x^3}{1 + 1.392x + 0.5121x^2 + 0.03944x^3},$$  \hspace{1cm} (8)$$

and $\phi(2.13) = 0.91$.

In the high-redshift limit, $z \gg 1$, I get the simple result,

$$f_{\text{max}}(z) = \frac{15.93 \text{ erg s}^{-1} \text{ cm}^{-2}}{(1 + z)^2[1 - \sqrt{1.21/(1 + z)}]^2}. $$  \hspace{1cm} (9)$$

This flux limit can be used to set an upper limit on the redshift of a source with an unknown origin.

For comparison, a flux of $\sim 15$ erg s$^{-1}$ cm$^{-2}$ is generated by local blackbody radiation at a temperature of 23 K, about ten times hotter than the cosmic microwave background today.

The highest luminosities for astrophysical sources are expected to occur during the formation of compact objects, in the form of gravitational waves or a $\gamma$-ray burst for a black hole or neutrinos for a neutron star. A violation of the limit in equation (8) for an isotropic, self-gravitating source with a known redshift $z$, would flag new physics.

The redshift of a cosmological source can be inferred from the spectral lines of its host galaxy or the Ly$\alpha$ absorption imprinted by the intergalactic medium.

The limit in equation (8) should be multiplied by a correction factor, $f_\Omega = (4\pi/\Delta\Omega)$, for a source radiating its energy into a limited solid angle $\Delta\Omega$.

### 3. IMPLICATIONS OF MODIFIED INERTIA AT LOW ACCELERATIONS FOR ROCKETS

MOdified Newtonian Dynamics (MOND) was proposed by Milgrom four decades ago (Milgrom 1983) to explain the flat rotation curves of galaxies and the baryonic Tully-Fisher relation (Milgrom 2020; McGaugh 2012; McGaugh et al. 2021). An attractive interpretation of MOND is that at accelerations of magnitude, $a \ll a_0 = 1.2 \times 10^{-8}$ cm$^{-2}$, the inertia of an object of mass $m$ satisfies a modified equation of motion in response to a force $F$ (Milgrom 2011, 2015),

$$m \frac{a^2}{a_0} = F.$$  \hspace{1cm} (10)$$

Below I consider the implications of modified inertia for a rocket whose fuel burns so as to produce a steady low-acceleration, $a \ll a_0$. 

The force (momentum delivered per unit time) acting on a rocket, is given by the mass ablation rate, $\dot{m}$, times the exhaust speed of the ablated gas relative to the rocket, $v_{\text{exh}}$:

$$F = -\dot{m}v_{\text{exh}}. \quad (11)$$

For a constant acceleration, the solution to equations (10) and (11) is,

$$\left( \frac{m_{\text{initial}}}{m_{\text{final}}} \right) = \exp \left\{ \left( \frac{a}{a_0} \right) \left( \frac{v_{\text{final}} - v_{\text{initial}}}{v_{\text{exh}}} \right) \right\}, \quad (12)$$

where the subscripts ‘initial’ and ‘final’ refer to the initial and final values of the rocket mass and speed. This result differs from the standard Tsiolkovsky solution to the rocket equation (Tsiolkovsky 2000) by the suppression factor $(a/a_0)$ in the exponent. Whereas the amount of fuel that needs to be carried grows exponentially with terminal speed in the standard Tsiolkovsky solution, a modified inertia offers the prospects of reaching high speeds by carrying much less fuel. This allows for intergalactic travel at a modest fuel-to-payload mass ratio.

As a concrete example, consider an intergalactic journey at a final speed of $v_{\text{final}} \sim 300 \text{ km s}^{-1}$, an order of magnitude faster than the rockets launched so far by humans. For standard chemical fuel, this terminal speed exceeds the exhaust speed by a factor $(v_{\text{final}}/v_{\text{exh}}) \sim 10^2$ (Gilster 2004). Thus, in order to achieve this terminal speed through an average acceleration magnitude $(a/a_0) \sim 0.01$ in free space, the required fuel mass would be comparable to the payload mass, $(m_{\text{initial}} - m_{\text{final}}) \sim 1.7m_{\text{final}}$. At this acceleration, the above terminal speed is obtained over a timescale, $t \sim 8\text{Gyr}$, comparable to the remaining lifetime of the Sun. During this time, the rocket would be able to traverse a distance $\frac{1}{2}at^2 \sim 1.2 \text{ Mpc}$, all the way to the edge of the Local Group of galaxies. Of course, additional fuel would be needed to overcome the binding energy of the Earth, the Sun and the Milky-Way galaxy.

The validity of the modified rocket equation can be tested by launching our own low-acceleration rocket or by finding low-acceleration rockets which arrived to our vicinity from great distances. It is unclear which approach is more likely to bear fruit as the first direct test of the modified inertia interpretation of MOND.

While escaping from the Earth, the Sun and the local Galactic environment, a rocket would need to overcome gravitational accelerations in excess of $a_0$. However, it is the net acceleration that counts in MOND, and so the rocket engine can be designed to produce just a little above what is needed to escape and stay in the MOND acceleration regime. This requires fine tuning of the rocket thrust, but is possible.

4. THE CMB DIPOLE IN MOND

The dipole anisotropy of the Cosmic Microwave Background (CMB) corresponds to a velocity of $\sim 300 \text{ km s}^{-1} = 10^{-3}c$ (Ferreira & Quartin 2021). It is commonly assumed that this velocity is induced by gravity across cosmic scales, as a result of
an average cosmic acceleration of, \( a \sim 10^{-3}H_0c \), over the age of the Universe \( \sim H_0^{-1} \), where \( H_0 \sim 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \) is the present-day Hubble constant (Freedman 2021).

This acceleration \( a \) of our cosmic neighborhood is by lower by a factor of \( \sim 5 \times 10^{-3} \) than the threshold acceleration, \( a_0 = 1.2 \times 10^{-8} \text{ cm s}^{-2} \sim 0.2H_0c \), in Modified Newtonian Dynamics (MOND) (Milgrom 2020). Hence, in MOND - the gravitational acceleration \( g \) required to induce the CMB dipole is,

\[
g \sim \left( \frac{a^2}{a_0} \right) \sim 2.5 \times 10^{-5}H_0c. \tag{13}
\]

Interestingly, this gravitational acceleration could result from a primordial amplitude of density perturbations on the scale of the cosmic horizon, \( \delta \sim (g/H_0c) \sim 2.5 \times 10^{-5} \), comparable to the amplitude of primordial fluctuations on horizon scales (Peebles 1993).

A nearby perturbation of a larger amplitude, like a supercluster, would induce within MOND a much larger CMB dipole than observed. Local galaxy survey do not converge as of yet to the observed dipole direction and amplitude (Loeb & Narayan 2008; Maartens et al. 2018).

5. QUANTUM TUNNELING OF FUZZY DARK MATTER OUT OF SATELLITE GALAXIES

The axion explains the lack of observed CP violation in quantum chromodynamics and is also an attractive dark matter candidate (Peccei & Quinn 1977; Weinberg 1978; Wilczek 1978). Ultra-light axions (ULAs) with masses \( \sim 10^{-22} \text{ eV} \), also known as fuzzy dark matter (Hu et al. 2000; Hui et al. 2017; Visinelli & Vagnozzi 2019; Rogers & Peiris 2021), are of particular interest in relieving small-scale challenges to the cold dark matter paradigm, stemming from discrepancies between observations and simulations of galaxies (Bullock & Boylan-Kolchin 2017).

Dwarf galaxies (DG) in the halo of the Milky-Way galaxy are subject to stripping by the gravitational tidal force (Fattahi et al. 2018; Gajda & Lokas 2016; Lokas 2020; Genina et al. 2022; Errani et al. 2022). To leading order, the tidal force scales in proportion to the distance from the DG center, \( r \), implying a tidal potential that scales as \( r^2 \). This modifies the binding gravitational potential of an isolated DG, \( \phi(r) \). Along the axis connecting the two galaxies, it yields a net potential,

\[
V(r) = m_a \left[ \phi(r) - \sigma^2 \left( \frac{r}{r_t} \right)^2 \right], \tag{14}
\]

where \( \sigma \) is the characteristic 3D velocity dispersion of the DG and \( r_t \) is the tidal radius. Classically, dark matter particles at \( r > r_t \) are stripped from the DG. But quantum-mechanical tunneling allows particles which are classically-bound to leak through the gravitational potential barrier and escape from \( r < r_t \) as a result of the extended tail of their wavefunction. This constitutes a new source for evaporation of dark matter particles with a small mass, such as ULAs.
The characteristic escape timescale of ULAs from $V(r)$ due to quantum-mechanical tunneling is,
\[ T_{\text{esc}} \sim \left( \frac{r_t}{\sigma} \right) \exp \left\{ -\frac{r_t}{\lambda_a} \right\}, \tag{15} \]
and
\[ \lambda_a = \frac{h}{2\sqrt{m_a^2|\langle \phi \rangle|}}, \tag{16} \]
with the virial theorem implying that the average kinetic energy of the bound particles is roughly half of their average gravitational binding energy, namely $\langle \phi \rangle \sim -\sigma^2$, and so
\[ \lambda_a = \left[ \frac{1 \text{ kpc}}{(m_a/10^{-22} \text{ eV})(\sigma/10 \text{ km s}^{-1})} \right]. \tag{17} \]

Given that some dark-matter-rich DGs in the Milky-Way halo have $r_t \lesssim 0.5 \text{ kpc}$, $\sigma \lesssim 5 \text{ km s}^{-1}$ (Lokas et al. 2011; Gajda & Lokas 2016; Lokas 2020; Genina et al. 2022; Errani et al. 2022), and $(r_t/\sigma) \lesssim 10^8 \text{ yr}$, their possession of dark matter over a Hubble time implies $T_{\text{esc}} \gtrsim 10^{10} \text{ yr}$ and therefore $m_a \gtrsim 2 \times 10^{-21} \text{ eV}$, based on equations (19-22).

This new constraint based on inevitable escape resulting from quantum-mechanical tunneling, rules out the preferred mass range for ULAs as dark matter.

6. GRAVITATIONAL WAVE ACCELERATION TO RELATIVISTIC ENERGIES

Consider a relativistic charged particle with a mass $m$, a charge $q$, a velocity vector $\mathbf{v} = \beta c$ and a Lorentz factor $\gamma = (1 - \beta^2)^{-1/2}$, that gyrates at the cyclotron frequency, $\Omega_c = (qB/mc)$ in a uniform magnetic field along the $z$-axis, $\mathbf{B} = B\hat{z}$. If the cyclotron frequency resonates with the Doppler shifted frequency of a wave propagating along the magnetic field direction, the particle would witness steady acceleration at a fixed phase of the wave crest.

For a transverse wave propagating at the speed of light, $c$, the Doppler-shifted cyclotron resonance is given by,
\[ \Omega_c = D\omega, \tag{18} \]
where $D \equiv \gamma(1 - \beta_z)$ is the Doppler factor along the $z$-axis (Rybicki & Lightman 1986), and $\omega$ is the wave frequency in the background frame of reference.

The relativistic equation of motion of the charged particle in the presence of either an electromagnetic wave (Loeb & Friedland 1986; Loeb et al. 1987) or a gravitational wave (Servin et al. 2001) propagating along the $z$-axis, admits the same identity,
\[ \frac{d\gamma}{dt} = \frac{d(\gamma \beta_z)}{dt}. \tag{19} \]
This implies the remarkable result that the Doppler factor $D = \gamma(1 - \beta_z)$ is a constant of motion, guaranteeing that the resonance condition in equation (18) will be maintained at all times if it is satisfied initially, even as the particle gains energy.
Under resonance, the Lorentz factor of a relativistic particle with $\gamma \gg 1$ grows steadily over time,

$$\frac{d\gamma}{dt} = \Omega_c \alpha,$$

where for an electromagnetic wave (Loeb & Friedland 1986):

$$\alpha_{EM} = \sqrt{\frac{2}{\gamma}} \times \left( \frac{qA}{mc} \right),$$

with $A$ being the vector potential. For a gravitational wave (Servin et al. 2001),

$$\alpha_{GW} = 2h,$$

with $h$ being the dimensionless wave amplitude.

The electromagnetic wave case serves as the basis for a novel acceleration scheme, the so-called “autoresonance laser accelerator” (Loeb & Friedland 1986). Quasi-neutrality is perfectly maintained in a symmetric electron-positron plasma (Loeb et al. 1987).

Equations (20) and (22) imply that a plane-parallel gravitational wave of a constant amplitude $h$ propagating along a constant magnetic field $B$, would accelerate charged particles at a constant rate to arbitrarily high energies.

However, for astrophysical sources of gravitational waves, the wave amplitude $h$ declines inversely with distance from the source. Given a magnetic field $B$ oriented radially from the source over a coherence length $\ell$, equation (20) implies that the particle’s Lorentz factor would reach a maximum value of,

$$\gamma_{\text{max}} \sim 1 + 2h\Omega_c \left( \frac{\ell}{c} \right).$$

Since $2h \lesssim (R_{\text{Sch}}/\ell)$ (Shapiro & Teukolsky 1986), we get

$$\gamma_{\text{max}} \lesssim 1 + \Omega_c t_{\text{Sch}},$$

where $t_{\text{Sch}} = (R_{\text{Sch}}/c) = 10^{-4} \text{ s} \times (M/10M_\odot)$ is the light crossing-time for the Schwarzschild radius $R_{\text{Sch}} = (2GM/c^2) = 30 \text{ km} \times (M/10M_\odot)$, of a gravitational wave source of total mass $M$.

The cyclotron frequency for electrons is $\Omega_{c,e} = 180 \text{ Hz} \times (B/10\mu\text{G})$ (whereas for protons, $\Omega_c$ is smaller by the particle mass-ratio of $1.836 \times 10^3$), can resonate with the frequency of gravitational waves generated in the final coalescence phase of binaries composed of stellar-mass black holes or neutron stars, which produce $\omega \sim 10^4$ Hz (Cahillane & Mansell 2022; Vajente 2022).

Under favorable conditions, the cyclotron resonance could boost the energies of relativistic electrons or protons in the plasma surrounding compact gravitational-wave sources. If the magnetic field originates from the source - as expected in the case
of neutron star mergers, its dipole amplitude would decline inversely with distance cubed, $B \propto \ell^{-3}$, out to the scale where the interstellar magnetic field will dominate.

The autoresonant acceleration by gravitational waves can heat relativistic electrons or protons in the vicinity of mergers of compact objects. This, in turn, could trigger synchrotron emission by the accelerated electrons that would result in an electromagnetic counterpart to the gravitational wave signal.

In principle, the cyclotron autoresonance could potentially lead to electromagnetic afterglows of the type reported for the black hole merger GW150914 (Loeb 2016; D’Orazio & Loeb 2018) or the neutron star merger GW170817/GRB170817A (Mooley et al. 2022). Detailed modeling is needed for the expected electromagnetic counterpart in specific environments.

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