A Space Mission to Test MOND and the Pioneer Anomaly

Abstract~~.~~

In light of current efforts to understand the Pioneer Anomaly, ~~(Anderson et al., 1998, 2002a, 2002b, 2002c)~~ we offer a testable explanation involving m~~M~~odified Newtonian d~~D~~ynamics (MOND)~~(Milgrom 1994)~~. We ~~are~~ suggest that radial trajectories~~,~~ in otherwise unmodified gravitational potentials~~,~~ introduce a~~s~~ modified inertia responsible for dynamic anomalies ~~dynamical~~. As e~~E~~xamples of radially evolving systems, we examine the Pioneer Anomaly~~,~~ and the cosmological acceleration observed using Type Ia supernovae ~~(Riess et al., 1998; Perlmutter et al. 1999a, 1999b)~~. We find that MOND predicts observable effects, which current ~~laboratory searches for~~studies of modified inertia (i.e., the s~~S~~trong e~~E~~quivalence p~~P~~rinciple) ~~has not been sensitive to~~do not detect. We describe how the addition of a second space ~~-~~probe to the ~~proposed Anderson et al.~~ Pioneer Anomaly mission proposed by Anderson et al. would constrain the prevailing MOND models.

Commented [CP1]: The style guide of your target journal, JCP, does not allow citations in the abstract, so I have removed them.

Commented [CP2]: Please consider determining whether the mission has a name, rather than referring to it by the PI's name.

Introduction

Anderson et al. (1998, 2002a) ~~finds have~~ found that the Pioneer 10, Pioneer 11, Galileo, and Ulysses deep space probes shared an anomalous, constant acceleration of magnitude $|\overrightarrow{a_P}| = (8.74 \pm 1.33) \times 10^8$ cm/s/s, directed radially toward~~s~~ the Sun. This “~~``~~Pioneer Anomaly”~~"~~ is apparently not ~~because of~~due to mission systematics (Anderson et al., 2002b; Murphy et al., 1999; Katz et al., 1999; Anderson et al., 1999a, 1999b) and may require new physics ~~in order~~ to be accurately model~~l~~ed. ~~-~~We consider an intriguing explanation involving new physics: the ~~—~~m~~M~~odified Newtonian d~~D~~ynamics (MOND) theory, ~~due to~~developed by Milgrom (1983, 1986, 1989; Bekenstein & Milgrom, 1984).

We ~~will~~ employ the MOND formalisms of modified inertia so ~~that~~that the ~~-~~dynamic~~al~~ bodies move in trajectory-dependent effective potentials. MOND is parameterized by a characteristic acceleration, $a_0 {\sim} 10^{-8}$ cm/s, which is usually small compared to the expected Newtonian acceleration, a_N.

The m~~M~~agnitude of the MOND contribution~~s~~ to~~o~~ observable dynamics ~~are~~ is given by the heuristic function $\mu(a/a_0)$, ~~for which~~where $\mu \approx 1$ when $a/a_0 \gg 1$ and $\mu \approx a/a_0$ when $a/a_0 \leq 1$. In this paper, we seek~~,~~ to discover a dynamical dependence in~~:~~ the vector *direction* of a trajectory;~~:~~ we suggest an explanation for the Pioneer Anomaly involving MOND effects on *radial* trajectories (i.e., $v \cdot a \approx 1$).

~~Already~~ Anderson et al. (2002c) ~~have~~ previously~~s~~ described a deep space probe mission capable ~~for sensitively figuring out,~~of detecting the magnitude of the Pioneer Anomaly with high sensitivity. However, since the cause~~,~~ of the a~~A~~nomaly is unknown, this mission ~~has a~~is purely empirical in nature. Here, we describe (1) an explanation for the Pioneer Anomaly ~~involving~~ using MOND and (2) an easy addition ~~of~~ to the Anderson et al. mission to test our MOND hypothesis.

The Equivalence Principle

The s~~S~~trong e~~E~~quivalence p~~P~~rinciple (SEP) says that the gravitational mass, m_g, and ~~the~~ inertial mass, m_i, of a body are ~~—~~identical. Experiments to verify the SEP typically quantify the ~~$\eta \equiv \Delta a/a$~~ Eö~~o~~tvö~~o~~s parameter, $\eta \equiv \Delta a/a$, between ~~the~~ attractive and dynamic~~al~~ accelerations. Su et al. (1994) and Smith et al. (2000) have observed ~~Laboratory~~laboratory-scale masses ~~have been observed (Su et al., 1994; Smith et al., 2000) to hav~~of~~e~~ $\eta < 10^{-13}$. The i~~I~~nteractions ~~about~~ of self-gravitating bodies ~~determine~~ are a special problem (Anderson et al., 1996), ~~and~~ having a ~~it's~~the current observational limit ~~is~~ of $\eta < 10^{-6}$ (Milani et al., 2002), although the Earth–~~-~~Moon system has ~~an~~ $\eta < 10^{-13}$ (Anderson & Williams, 2001).

Commented [CP3]: When a theory, model, or procedure is named after two or more individuals, their names are conventionally joined using an en dash. The same rule applies whenever the elements of a compound are considered equivalent, so parent–child relationship, cost–benefit analysis, etc., use an en dash rather than a hyphen.

Current experimental designs ~~to~~ that ~~aretest~~test the SEP do not consider trajectory dependence. ~~By performing a~~A literature review revealed~~, we found~~ that experiments ~~and, iI facted~~~~the and foundexamineinvolve~~ predominantly involved azimuthal trajectories. For example, the experiments of Su et al. (1994) ~~SEP experiments~~ test~~-~~ed horizontal accelerations in a terrestrial laboratory;~~.~~ the ~~The~~ sensitivity~~e~~ limit of~~n~~ η wa~~i~~s measured for accelerations toward~~s~~ the Sun using masses orbiting ~~with~~ the Earth on azimuthal trajectories. Measurements of the SEP ~~in~~ of ~~the~~ ~~a~~ self-gravitating objects, ~~like~~ such as ~~a~~ planets (Anderson et al., 1998, 1996; Milani et al., 2002; Anderson & Williams, 2001) and ~~the~~ neutron stars (Darmour & Schaefer, 1991), ~~is~~ are also limited to azimuthal orbital trajectories ~~azimuthal orbital~~.

Commented [CP4]: Edits to this sentence may have changed your intended meaning; please review before accepting changes.

Radial ~~-~~trajectory experiments (Kuroda & Mio, 1989; Dittus & Mehls, 2001; Reasenberg & Phillips, 2001)~~,~~ present ~~the~~ a greater experimental challenge (Blaser, 2001). ~~that has~~ These measurements have yielded a less sensitive upper limit, $\eta \leq 10^{-9}$. ~~They c~~Based on these results, we would not ~~expects~~expect that these laboratory experiments could detect ~~that~~ the Pioneer

Anomaly ~~would to be detectable in this these laboratory experiments~~.

MOND

~~In~~ To ~~trying to~~ modify the inertia, we ~~don't~~ want to alter the Newtonian kinetic ~~action~~ energy:

Commented [CP5]: Edits to this sentence may have changed your intended meaning; please review before accepting changes.

$$S_N = \frac{1}{2} m \int v^2 dt$$

such that a radial trajectory dependence is introduced while Newtonian dynamics are still recovered in the limit $a_0 \rightarrow 0$.

This is ~~most simply~~ accomplished most simply with an ~~action~~ equation of the form:

$$S_M = \frac{1}{2} m \int \left[1 - \underbrace{\mu \frac{a_0}{a} \, (\hat{v} \cdot \hat{a})}_{M_S} \right] v^2 dt$$

The additional factor, M_S, vanishes for any near-circular orbit of azimuthal trajectory $\boldsymbol{v} \cdot \boldsymbol{a} \approx 0$, ~~which~~ such as those of ~~the,~~ planets. Indeed, Anderson et al. (1998) ~~are~~ have calculated that any *universally* e~~a~~ffective property of the gravitational force~~,~~ capable of producing the Pioneer deceleration would already ~~be~~ have been ~~sobserved~~observed in the orbital motions of the planets. ~~(Also~~In addition, this form of M_S ~~doesn't~~ does not produce~~s~~ effects ~~for~~ on the orbits of stars in galaxies~~, and of~~ or for galaxies in clusters, as was the original intention of MOND. These effects ~~This~~ could be included in a more complicated form of M_S~~-~~, but we consider these “~~``~~dark matter”~~''~~ issues (Castillo-Morales & Schindler, 2003) to be ~~a separate problem not of interest here~~outside the scope of this work.~~)~~

Commented [CP6]: Please consider whether “sophisticated” might be a better word choice here.

Our modified ~~action~~ equation predicts MOND effects for *all*~~{\em all}~~ radial trajectories. For ~~the~~ large accelerations~~-~~, $a/a_0 \gg 1$~~`$a/a_0 \gg 1$,`~~, $\mu \approx 1$, and $M_S \propto a_0/a$. For the Pioneer Anomaly, we expect $M_S \sim 10^{-4}$, as has been observed. Furthermore, the anomalous Pioneer acceleration, a_P, is *constant*, meaning $\eta_P \propto r^2$, as expected ~~from~~ for ~~the~~an M_S ~~for~~ with a constant a_0 and $a = GM/r^2$. For small accelerations, $a/a_0 \leq 1$, $\mu \approx a/a_0$, and $M_S \approx 1$. ~~You~~ This effect can also ~~use this to~~ explain the anomalously faint, high-~~-~~redshift Type Ia supernovae (SNIa) observed by Riess et al. ~~-~~(1998) and Perlmutter et al. (1999a, 1999b) ~~is due to~~as small-acceleration MOND effects on the radial trajectories of the cosmological expansion.

Table 1. Accelerations

Body	Potential	η	a_N (cm s^{-2})	a_0/a
azimuthal systems with $\hat{v} \cdot \hat{a} \approx 0$				
Moon	Earth	$< 10^{-13}$	0.3	3.3×10^{-8}
SEP lab	Sun	$< 10^{-13}$	0.6	1.7×10^{-8}
Mars	Sun	$< 10^{-6}$	0.3	3.3×10^{-8}
star	galaxy	~ 1	2×10^{-8}	0.5
galaxy	cluster	~ 1	2×10^{-10}	50
radial systems with $\lvert\hat{v} \cdot \hat{a}\rvert \approx 1$				
Pioneer	Sun (at 30 AU)	-10^{-4}	7×10^{-4}	2×10^{-5}
SEP lab	Earth	$< 10^{-9}$	9.8×10^{2}	10^{-11}
cluster	Universe	~ 1	7×10^{-8}	0.2

~~the~~ Table 1 summarizes the MOND regime of various ~~known~~ experimentally determined accelerations. ~~Of the interest here are — the~~ The final three ~~entries~~ rows~~, which~~ comprise our knowledge of ~~the~~ radial trajectories.

The rightmost column lists~~ the value of~~ a_0/a, which is the detection threshold of M_S in the strong acceleration limit. Anderson et al. ~~say~~ have suggested that detecting the Pioneer Anomaly requires~~d~~ acceleration measurements accurate to at least one part in 10^6, consistent with our predicted MOND contribution. Furthermore, we ~~may~~ predict that radial ~~-~~trajectory SEP experiments in terrestrial laboratories will detect MOND effects when the accuracy~~ies~~ reaches one part in 10^{12} (which is still three orders of magnitude away). However, the~~The~~ manifestation of MOND ~~manifestation~~ in the Pioneer Anomaly~~, on the other hand,~~ is readily testable with current technology.

Commented [CP7]: Please confirm that this number is consistent with Table 1.

The Experiment

Anderson et al. (2002c) have~~s~~ proposed ~~the~~ an experiment to further characterize the Pioneer Anomaly. Since the proposed mission uses a radial trajectory, we ~~offer~~ suggest a modification to test our MOND hypothesis: u~~U~~se ~~a~~ twin spacecraft~~spacecrafts~~ in ~~the~~ a near-circular orbit. Placing ~~a twin~~one space probe on an azimuthal trajectory~~,~~ should ~~simply~~ demonstrate the radial dependence of the MOND interpretation of the Pioneer and SNIa anomalies. As originally planned, t~~T~~he Anderson et al. radial mission ~~-~~would ~~sensitively~~ probe the known anomaly with high sensitivity, while our azimuthal mission should return a null result. The azimuthal mission~~, like the a planets,~~ will have a near-circular trajectory, like that of a planet, that is presumably unaffected by the proposed inertial MOND contributions. Since the Pioneer Anomaly is best observed beyond ~20 AU, we suggest that the two missions share radial trajectories out to the orbit of Neptune (30 AU), at which point the azimuthal mission can be gravitationally deflected by Neptune into a bound, low-eccentricity orbit (Fig. 1). The deflected orbit may be chosen to be outside of the ecliptic plane (to characterize external heliospheric accelerations, ~~to~~ probe the solar system potential at various angles, or simply ~~to~~ study the heliosphere at unprecedented radii and latitudes).

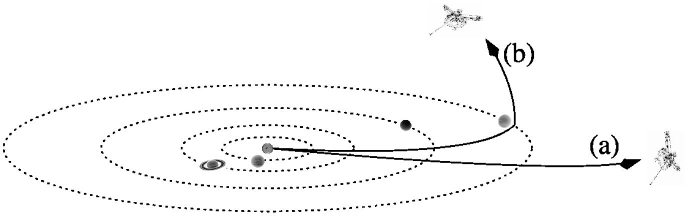

Figure 1. Suitable mission trajectories for (a) the Anderson et al. probe and (b) the azimuthal twin. The planetary positions are correct for June 2003.

The shared radial portions~~,~~ of the missions should provide reliable accounts~~a reliable accounts~~ of (1) the measurements of the anomaly and (2) the similarity of the two spacecraft~~s~~. After ~~a~~ deflecti~~ons~~ng from Neptune, the predicted disappearance of the anomaly in the azimuthal probe would ~~provides~~provide significant evidence~~s~~ against the interpretation of the anomaly as an on-board systematic effect. ~~of the twin probes.~~

The trajectory dependence in the ~~probe's' ~~accelerations ~~s~~of the probes would be easily detectable using standard telemetry. In addition, the large proper motion of the azimuthal mission would be detectable using very long baseline radio interferometric techniques, allowing for independent verification of the telemetry calculations (Anderson et al. 2002b).

Conclusion

We find that the radial ~~-~~trajectory ~~phenomenas~~phenomena are subject to deviations from Newtonian dynamics due to MOND-~~-~~modified inertia. The term M_S~~-~~, which modifies the kinetic action, possesses a simple algebraic form ~~which~~ that follows naturally from the trajectory constraints and existing experimental limits.

Currently, this anomaly is best suited ~~for~~ to observation in ~~the a~~ space-borne experiments.

We propose testing ~~s to test,~~ MOND effects in the vicinity of our Sun using the space flight described by Anderson et al. with the addition of a twin probe deflected into a closed orbit at Neptune.