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Review of the PhD dissertation

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Outer Solar System in Milgromian Dynamics

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Title: Outer solar system in Milgromian dynamics

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Abstract: Milgromian dynamics (MD) provides an excellent physical description of the observed galaxies. We review motivation for MD and its current status as a physical theory. The most developed theories of MD are those of the modified gravity type, and at the same time, the most profound tests of modified gravity theories have always been those in the solar system. In this thesis, the implications of MD for the weak and intermediate-field regions of the solar system, like the Oort cloud and the Kuiper belt, were investigated in detail for the first time. The thesis consists of three projects. All three projects somehow revolves around the influence of the external field effect, which comes from inherent non-linearity of MD, on the internal solar system dynamics. In the first one, the Oort cloud hypothesis is reconsidered in the framework of MD. In the second, a hypothesis that the puzzling orbital characteristics of extreme trans-Neptunian objects are a consequence of the external field effect is investigated; the extreme trans-Neptunian objects are Kuiper belt objects in orbits beyond Neptune and having semimajor axes between 150 and 1500 au. In the third project, we study an imprint of the external field effect on the Oort cloud comets aphelia distribution on the celestial sphere. We show that various puzzling solar system observations could be elucidated in MD. Predictions that can be tested against observations in the future are made.

Keywords: gravitation – inertia – Kuiper belt – Oort cloud

Summary of the dissertation

Galaxies obey scaling laws like the baryonic Tully-Fisher relation (McGaugh et al. 2000), the Faber-Jackson relation (Faber and Jackson 1976), and the mass-discrepancy-acceleration relation (Sanders 1990; McGaugh 2004). These are the laws of nature, much like the Kepler's laws of planetary motion. All these laws relate the distribution of stars and gas in galaxies with their underlying dynamics and thus are naturally explained if the observed stars and gas are the only source of the gravity in galaxies. There is the missing acceleration problem in Newtonian dynamics, manifesting e.g. through rotation curves of rotationally-supported galaxies which are flat instead of falling as expected, hence the standard dynamics must be somehow modified. The similar situation happened many times in the history of physics (e.g. the generalizations introduced by special relativity, general relativity, quantum mechanics, etc.) thus is by no means extraordinary or such approach exotic. Moreover, the wealthy data on galaxies show in many independent ways the existence of a special acceleration scale a_0, $a_0 \sim cH_0 \sim c^2\Lambda^{1/2} \sim 10^{-10}$ m s^{-2}; see e.g. Famaey and McGaugh (2012). In galaxies, everything happens as if in the weak-field regime, i.e. at low accelerations ($a \ll a_0$), typical in galaxies, the true dynamics was space-time scale invariant (Milgrom 2009b), contrary to Newtonian dynamics and general relativity which are not. This is the essence of the Modified Newtonian Dynamics (MOND) paradigm proposed by Milgrom (Milgrom 1983). Any successful physical framework, whether hypothesising existence of dark matter particles in the standard Newtonian framework or somehow modifying the standard dynamics instead, must account for the striking regularity apparent in the data on galaxies. Here MOND and its parent physical theories, referred to collectively as Milgromian dynamics (MD), stand out as they predicted in advance and in detail many aspects of the galactic phenomenology we now fully recognise; see e.g. Famaey and McGaugh (2012). As yet another example, recently it was shown that in rotationally-supported galaxies, the centripetal acceleration measured by the rotation curve, g_{obs}, strongly correlates with that predicted by the observed distribution of stars and gas, g_{bar} (McGaugh et al. 2016). The correlation is very tight and is consistent with zero intrinsic scatter, i.e. consistent with being a functional dependence, $g_{obs} = g_{obs}(g_{bar})$. This is natural if the stars and gas are the only source of the gravity. Moreover, the relation between g_{obs} and g_{bar} is of the form exactly predicted by MOND: at accelerations $a \gg a_0$, we have $g_{obs} = g_{bar}$, while at $a \ll a_0$, $g_{obs} = \sqrt{g_{bar}a_0}$, and the dynamics is space-time scale invariant. The both regimes are smoothly connected by some interpolating function.

The most developed theories of MD are those of the modified gravity type, and at the same time, the most profound tests of the modified gravity theories have always been those in the solar system. Milgromian dynamics is not allowed to violate the solar system data so these could be used to constrain the freedom in MD theories. The freedom stems in the interpolation between the deep-Newtonian and deep-MD, scale invariant, regime, as this does not follow from the theory as yet. In historical parallel, this is like when the Planck black-body function, interpolating between the classical, Rayleigh-Jeans, and the high-frequency, Wien, limit, was not known. The most stringent constraints on the interpolating function come from the radio-tracking data of the Cassini-spacecraft (Hees et al. 2014, 2016).

An important aspect of the modified gravity MD theories is that such theories break the strong equivalence principle. In the solar system, this means that objects orbiting the Sun are influenced, beyond its tidal effect, by the gravitational field of the Galaxy with magnitude $\sim a_0$ through the so called exter-

nal field effect (EFE) (Milgrom 1983; Famaey and McGaugh 2012). EFE in the solar system could be important even when the internal accelerations are not much below a_0 (Milgrom 2009a). Moreover, it attenuates the classical "enhanced gravity" effect of MD. In this thesis, the implications of MD for the weak and intermediate-field regions of the solar system, like the Oort cloud and the Kuiper belt, were investigated in detail for the first time. The thesis presents three projects.

I. Oort cloud of comets in Milgromian dynamics

We reconsidered the Oort cloud (OC) hypothesis in the framework of MD. The hypothesis originally hinges on the fact that the observed new comets entering the inner solar system have very low original Newtonian binding energies, corresponding to typical semimajor axes, a, of several tens kau (Oort 1950; Dones et al. 2004). The comets are always observed in the deep-Newtonian regime. Routinely, comets' positions and velocities, actual observables independent on the dynamical framework, are translated into Newtonian orbital elements.

We constructed a numerical model of the cloud embedded in the constant external field of the Galaxy assuming quasi linear theory of MOND (QUMOND) (Milgrom 2010). The MD potential was calculated on a grid using the fast-Fourier-transform technique and by taking advantage of the "phantom matter" approach (Milgrom 2010).

- We showed how the OC dimensions, and qualitatively, the operation of the planetary barrier, and the comet delivery, depend on the interpolation between Newtonian and MD regime. Importantly, for the interpolating functions allowed by the Cassini data, the observationally inferred OC is Newtonian in its size and operation of the planetary barrier.

- We demonstrated that even in the case when the classical, enhanced-gravity, effect of MD is negligible, attenuated by the external field of the Galaxy, the EFE could still provide a significant torque on orbits with semimajor axes from several hundred to few kau, i.e. on those orbits not significantly influenced by the Galactic tide. Regions of $a - e$ space, where e is eccentricity, forbidden in the Newtonian framework, could be populated with aid of EFE in MD. It is proposed that EFE might be responsible for direct injections of comets from the inner OC, as well as that Sednoids and high-a Centaurs might be members of the same population, just in different modes of their evolution driven by EFE. These ideas needs further detailed investigation.

A step further was taken in the next project. The qualitative analysis of the OC was followed by a more quantitative investigation of the extreme trans-Neptunian objects of the Kuiper belt in MD.

II. Extreme trans-Neptunian objects in Milgromian dynamics

Extreme trans-Neptunian objects (ETNOs) are defined as objects in orbits beyond Neptune and having $150 < a < 1500$ au. These objects are extraordinary as their orbits seem to be anisotropically oriented in space, especially those having $a > 250$ au (Trujillo and Sheppard 2014; Brown and Firth 2016; Batygin and Brown 2016). It is as if these objects have been systematically perturbed by some external force. Orbits of ETNOs Sedna and 2012 VP_{113} show yet another puzzle: they have extraordinarily high perihelion distances, both have q close to 80 au, while having low semimajor axes, both have $a \lesssim 500$ au. Even at heliocentric distances corresponding to the aphelion distances of Sedna and 2012 VP_{113}, the dynamical effect of Galactic tides and passing stars is weak, unable to torque out their perihelia from the planetary zone, where they were probably formed, to ≈ 80 au. We investigated a hypothesis that the puzzling orbital characteristics of ETNOs are a consequence of EFE in MD.

The dominant dynamical effect of MD in the ETNOs region is EFE. We modeled EFE as a quadrupole anomaly added to the Newtonian potential of the Sun. The strength of the quadrupole was parametrised with a constant parameter Q_2 (Blanchet and Novak 2011). The direction of the anomalous acceleration varies with time as the external gravitational acceleration from the Galaxy rotates with period of one Galactic year around the Sun. The constraints on the strength of EFE, $Q_2 = 3 \pm 3 \times 10^{-27}$ s^{-2} (nominal $\pm 1\sigma$ value) (Hees et al. 2014), coming from the analysis of the motion of the Cassini spacecraft, were taken into account.

- We showed that the orbits of Sedna and 2012 VP_{113} could be explained as a consequence of the action of EFE. Though, 2012 VP_{113} seems only marginally consistent with the pure EFE origin scenario if one adopts the Cassini constraints on Q_2.

- Assuming that either Sedna's or 2012 VP_{113}'s perihelion distance, or both, were torqued out solely with the aid of EFE, we found the lowest Q_2s capable to produce sufficient perihelion change during the age of the solar system. As the value of Q_2 is related to the interpolating function, the boundary Q_2s we found can be translated to constraints on the interpolating function.

- We showed that the long-term effect of EFE on primordial, initially randomised, ETNOs orbits is that it leads to non-uniform distribution of the orbital elements related to the orientation of an orbit in space (ω, Ω, i). Our simulations in MD shit robust clustering in the longitude of perihelion Ω, while only limited in the argument of perihelion ω. EFE also causes excitation in inclinations i.

- Assuming $Q_2 > 0$, we get the clustering in Ω with 180 deg offset from the observed clustering position. Contrary, with $Q_2 < 0$, the simulated clustering position is aligned with the observed one. Though, we note that none of the as-yet proposed interpolating functions give arise to negative Q_2.

- If we at the same time demand that the spatial orientation of orbits of ETNOs as well as the detachment of Sedna and 2012 VP_{113} are a consequence of the action of EFE, then Q_2 is required to acquire values that are highly unlikely (with probability $< 1\%$) in the light of the Cassini data. And even then the observed clustering in ω is not reproduced well by the pure EFE model.

In conclusion, while it is possible that the high perihelion distances of Sedna and 2012 VP_{113} could be caused by the EFE of MD, it seems improbable that the current data on spatial distribution of ETNOs orbits can be explained by the same simple model as well.

III. Oort cloud comets aphelia distribution in Milgromian dynamics

Aphelia of intermediate outer Oort cloud comets are distributed non-uniformly on the celestial sphere, showing a prominent concentration around the great circle centered at Galactic longitudes $L = -45$ and 135 deg (Matese et al. 1999; Matese and Whitmire 2011); the intermediate outer Oort cloud comets are defined as comets entering the planetary zone for the first time and having original semimajor axes between 15 and 35 kau. The non-uniformity is beyond that attributable to the classical injectors of comets, stellar encounters and the Galactic tides (e.g. Rickman et al. 2008), as well as the expected observational biases (Horner and Evans 2002).

In the framework of MD, we studied if there exist preferred orientations of orbits of OC bodies with the intermediate semimajor axes where their perihelia are more effectively reduced. We used an approximative analytical formula for QUMOND potential that is applicable at heliocentric distances where the gravity of the Sun is much smaller than the external field of the Galaxy, i.e. for $r \gtrsim 5500$ au. The used MD potential incorporates the gravity of the Sun and the external field from the Galaxy of constant magnitude and time-varying direction.

- We showed analytically for orbits in the Galactic equatorial region that such preferred locations, though varying with time, indeed exist.

- The fact that we do not observe non-uniformity also in the L distribution of high-a comets can be explained as a consequence of the fact that the influence of EFE weakens as a increases (shown analytically), while the influence of the Galactic tides grows stronger rapidly with increasing a. We backed up this claim by numerical experiments.

- In numerical simulations, we demonstrated the characteristic imprint of EFE on the distribution of aphelia of candidate OOC comets that migrated down to $r = 10\,000$ au. The candidate intermediate OOC comets were modeled as test particles starting isotropically distributed on the celestial sphere with a in range between 17 000 and 33 000 au and perihelia between $q = 17\,000$ au and $q = a$, where a is semimajor axis of a given particle's orbit. EFE induces a great-circle concentration (GCC) in L for the intermediate-a particles. The combined effect of EFE and tides leads to the distribution of aphelia having the characteristic features resembling those of the observed one. As the external field rotates around the Sun with period of one Galactic year, the longitude of the GCC of aphelia rotates with the same rate.

- The simulated GCC matches the position of the observed one at the time when the external field is about 60 deg behind the present-day orientation. The external field needs additional about 40 Myr to align with the present-day orientation.

- We found a single combination of a Cassini-allowed interpolating function and the Galactic parameters that leads to sufficiently strong EFE and as a consequence to the GCC in L. These findings are in concordance with the work of Paučo (2017), where we found that similarly strong EFE is needed to explain the large perihelion distances of Sedna and 2012 VP_{113}.

As a future prospect, it remains to be demonstrated that the distribution of aphelia of OC comets delivered into the inner solar system can be explained also quantitatively by the combined effect of EFE, Galactic tides, and passing stars, in the framework of MD. An important question is also whether the GCC induced by EFE matches the position of the observed one at the time of the actual injection into the inner solar system, i.e. when the external field has the present-day direction. To accomplish these tasks we would have to switch from the presented semi-analytical modeling to solving the QUMOND equations numerically. For this purpose we could use our own code (as in the project II), or the recently developed POR[1] code (Lüghausen et al. 2015), which enables us to take advantage of the adaptive mesh refinement technique.

[1]Phantom of RAMSES

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