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DISTANT EKOs

The Kuiper Belt Electronic Newsletter

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NEWS & ANNOUNCEMENTS

Welcome to the last pre-Pluto-exploration edition of *Distant EKOs*, the Kuiper belt newsletter. Coincidentally, this is issue #99, where "9" has been a symbolic number for Pluto. Regardless of what definition you use now, Pluto historically has been the ninth planet, delineating the "edge" of our solar system and defining the frontier of what many people might think of as our neighborhood. And I use the term "neighborhood" much in the sense of how you might have used it as a child: the part of your world that you could *personally* explore, where you could walk past initially mysterious but eventually familiar houses, know the names and quirks of your neighbors, look under rocks, touch and feel, and discover new things on your own while letting curiosity lead where you go. And we have been exploring our solar neighborhood much this way for the past five decades.

But then we learned that odd little house at the end of the street was actually the sentinel to a bigger world.

We had discovered the Kuiper belt back in 1930, but we just didn't realize it at the time. Whenever I'm asked the inevitable question about whether Pluto is a "planet" or not, I say that it has Dual Citizenship — it was the last discovered planet and the first discovered Kuiper belt object. And now we finally are finishing the task we started in the 1960's, completing the reconnaissance of the historical solar system, and simultaneously making the first detailed study of a member of the Third Zone. That iconic stamp of Pluto with the words "not yet explored" will become a quaint collector's item.

I look forward to *Distant EKO's* #100, the first post-Pluto flyby issue, and all the subsequent issues that will be revealing not just the new analyses of the amazing data to come back from New Horizons, but the fresh ideas and results of the new ground-based observations, the new measurements and calculations, models and simulations, origins scenarios, and daring space missions that will follow.

Joel Parker, editor of *Distant EKOs*

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A new solar system electronic newsletter has appeared on the scene:
You are invited to read, subscribe to, and participate in the Cometary Science Newsletter (CSN), dedicated to sharing and furthering cometary science. Contributions are invited from the astronomical and planetary science communities, including abstracts of papers accepted for publication in refereed journals, thesis abstracts, conference announcements, job announcements, or other relevant and brief scientific communications. Relevant topics include observational, theoretical, and laboratory work concerning comets, but also may include studies of associated phenomena, such as Centaurs, asteroid-comet transition objects, and debris disks.
For more information, to subscribe to monthly issue announcements, and to read prior issues online, visit the CSN homepage at:
`http://www.cometarysciencenews.org/`
Sincerely,
Mike Kelley, CSN Editor
University of Maryland

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There were 9 new TNO discoveries announced since the previous issue of *Distant EKOs*:

2006 SG415, 2006 SH415, 2007 FP51, 2012 YO9, 2014 FT71, 2014 FU71, 2014 FW71, 2014 FY71, 2015 FG345

and 14 new Centaur/SDO discoveries:

2007 FO51, 2007 LG38, 2007 LH38, 2007 LJ38, 2007 RZ326, 2008 AU138, 2014 FV71, 2014 FX71, 2015 HO171, 2015 HP9, 2015 HT171, 2015 HX10, 2015 KB157, 2015 KZ120

Reclassified objects:

2007 RM314 (TNO → SDO)
2001 FL193 (TNO → SDO)
2015 KB157 (Centaur → SDO)
2015 KZ120 (Centaur → SDO)

Objects recently assigned numbers:

2003 FK127 = (434194)
2005 CH81 = (434390)
2006 CJ69 = (434709)
2013 EK73 = (437313)
2013 TV158 = (437360)
2001 FN185 = (437871)
2002 GD32 = (437915)
2004 EH96 = (438028)

Objects recently assigned names:

2007 TY430 = Mors-Somnus

Deleted/Re-identified objects:

2014 FX43 = 2015 HT171

Current number of TNOs: 1372 (including Pluto)
Current number of Centaurs/SDOs: 456
Current number of Neptune Trojans: 12

Out of a total of 1840 objects:

662 have measurements from only one opposition
633 of those have had no measurements for more than a year
326 of those have arcs shorter than 10 days

(for more details, see: `http://www.boulder.swri.edu/ekonews/objects/recov_stats.jpg`)

PAPERS ACCEPTED TO JOURNALS

Resonant Interactions and Chaotic Rotation of Pluto's Small Moons

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Four small moons—Styx, Nix, Kerberos and Hydra—follow near-circular, near-equatorial orbits around the central 'binary planet' comprising Pluto and its large moon, Charon. New observational details of the system have emerged following the discoveries of Kerberos and Styx. Here we report that Styx, Nix and Hydra are tied together by a three-body resonance, which is reminiscent of the Laplace resonance linking Jupiter's moons Io, Europa and Ganymede. Perturbations by the other bodies, however, inject chaos into this otherwise stable configuration. Nix and Hydra have bright surfaces similar to that of Charon. Kerberos may be much darker, raising questions about how a heterogeneous satellite system might have formed. Nix and Hydra rotate chaotically, driven by the large torques of the Pluto-Charon binary.

Published in: Nature, 522, 45 (2015 June 4)

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Formation and Evolution of Pluto's Small Satellites

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Pluto's system of 5 known satellites are in a puzzling orbital configuration. Each of the four small satellites are on low-eccentricity and low-inclination orbits situated near a mean motion resonance with the largest satellite Charon. The Pluto-Charon binary likely formed as a result of a giant impact and so the simplest explanation for the small satellites is that they accreted from debris of that collision. The Pluto-Charon binary has evolved outward since its formation due to tidal forces, which drove them into their current doubly synchronous state. Meanwhile, leftover debris from the formation of Charon was not initially distant enough from Pluto-Charon to explain the orbits of the current small satellites. The outstanding problems of the system are the movement of debris outward and the small satellites location near mean motion resonances with Charon.

This work explores the dynamical behavior of collisionally interacting debris orbiting the Pluto-Charon system. While this work specifically tests initial disk and ring configurations designed to mimic the aftermath of the disruption of satellites by heliocentric impactors, we generally find that collisional interactions can help move material outwards and keep otherwise unstable material dynamically bound to the Pluto-Charon system. These processes can produce rings of debris whose orbits evolve rapidly due to collisional processes, with increasing pericenters and decreasing semimajor axes. While these rings and disks of debris eventually build satellites significantly further out than the initial locations of a disrupted satellite, they do not show a strong preference for building satellites in or near mean motion resonances with Charon under a wide array of tested conditions.

Published in: The Astronomical Journal, 150, 11 (2015 July)

For preprints, contact `kwalsh@boulder.swri.edu`

or on the web at `http://arxiv.org/abs/1505.01208`

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Impact and Cratering Rates onto Pluto

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The New Horizons spacecraft fly-through of the Pluto system in July 2015 will provide humanity's first data for the crater populations on Pluto and its binary companion, Charon. In principle, these surfaces could be dated in an absolute sense, using the observed surface crater density (# craters/km^2 larger than some threshold crater diameter D). Success, however, requires an understanding of both the cratering physics and absolute impactor flux. The Canada-France Ecliptic Plane Survey (CFEPS) L7 synthetic model of classical and resonant Kuiper belt populations (Petit et al. 2011, Gladman et al. 2012) and the scattering object model of Kaib et al. (2011) calibrated by Shankman et al. (2013) provide such impact fluxes and thus current primary cratering rates for each dynamical sub-population.

We find that four sub-populations (the $q < 42$ AU hot and stirred main classicals, the classical outers, and the plutinos) dominate Pluto's impact flux, each providing $\approx 15 - 25\%$ of the total rate. Due to the uncertainty in how the well-characterized size distribution for Kuiper belt objects (with impactor diameter $d > 100$ km) connects to smaller projectiles, we compute cratering rates using five model impactor size distributions: a single power-law, a power-law with a knee, a power-law with a divot, as well as the "wavy" size distributions described in Minton et al. (2012) and Schlichting et al. (2013). We find that there is only a small chance that Pluto has been hit in the past 4 Gyr by even one impactor with a diameter larger than the known break in the projectile size distribution ($d \approx 100$ km) which would create a basin on Pluto ($D \geq 400$ km in diameter). We show that due to present uncertainties in the impactor size distribution between $d = 1 - 100$ km, computing absolute ages for the surface of Pluto is entirely dependent on the extrapolation to small sizes and thus fraught with uncertainty. We show, however, what the ages would be for several cases and illustrate the relative importance of each Kuiper belt sub-population to the cratering rate, both now and integrated into the past. In addition, we compute the largest "fresh" crater expected to have formed in 1 Gyr on the surface of Pluto and in 3 Gyr on Charon (to 95% confidence) and use the "wavy" size distribution models to predict whether these largest "fresh" craters will provide surfaces for which portions of the crater production function can be measured should most of the target's surface appear saturated. The fly-through results coupled with telescopic surveys that bridge current uncertainties in the $d = 10 - 100$ km regime should eventually result in the population estimate uncertainties for the Kuiper belt sub-populations, and thus the impact fluxes onto Pluto and Charon, dipping to $< 30\%$.

We also compute "disruption timescales" (to a factor of three accuracy) for Pluto's smaller satellites: Styx, Nix, Kerberos, and Hydra. We find that none of the four satellites have likely undergone a catastrophic disruption and reassembly event in the past ≈ 4 Gyr. In addition, we find that for a knee size distribution with $\alpha_{faint} \leq 0.4$ (down to sub-km diameters), satellites of all sizes are able to survive catastrophic disruption over the past 4 Gyr.

To appear in: Icarus

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The Mutual Orbit, Mass, and Density of the Large Transneptunian Binary System Varda and Ilmarë

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From observations by the Hubble Space Telescope, Keck II Telescope, and Gemini North Telescope, we have determined the mutual orbit of the large transneptunian object (174567) Varda and its satellite Ilmarë. These two objects orbit one another in a highly inclined, circular or near-circular orbit with a period of 5.75 days and a semimajor axis of 4810 km. This orbit reveals the system mass to be $(2.664 \pm 0.064) \times 10^{20}$ kg, slightly greater than the mass of the second most massive main-belt asteroid (4) Vesta. The dynamical mass can in turn be combined with estimates of the surface area of the system from Herschel Space Telescope thermal observations to estimate a bulk density of $1.24^{+0.50}_{-0.35}$ g cm^{-3}. Varda and Ilmarë both have colors similar to the combined colors of the system, $B - V = 0.886 \pm 0.025$ and $V - I = 1.156 \pm 0.029$.

To appear in: Icarus

Preprints available at `http://www2.lowell.edu/~grundy/abstracts/2015.Varda-Ilmare.html`

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Jumping Neptune Can Explain the Kuiper Belt Kernel

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The Kuiper belt is a population of icy bodies beyond the orbit of Neptune. A particularly puzzling and up-to-now unexplained feature of the Kuiper belt is the so-called 'kernel', a concentration of orbits with semimajor axes $a \simeq 44$ AU, eccentricities $e \sim 0.05$, and inclinations $i < 5°$. Here we show that the Kuiper belt kernel can be explained if Neptune's otherwise smooth migration was interrupted by a discontinuous change of Neptune's semimajor axis when Neptune reached $\simeq 28$ AU. Before the discontinuity happened, planetesimals located at $\sim$40 AU were swept into Neptune's 2:1 resonance, and were carried with the migrating resonance outwards. The 2:1 resonance was at $\simeq$44 AU when Neptune reached $\simeq 28$ AU. If Neptune's semimajor axis changed by fraction of AU at this point, perhaps because Neptune was scattered off of another planet, the 2:1 population would have been released at $\simeq$44 AU, and would remain there to this day. We show that the orbital distribution of bodies produced in this model provides a good match to the orbital properties of the kernel. If Neptune migration was conveniently slow after the jump, the sweeping 2:1 resonance would deplete the population of bodies at $\simeq$45-47 AU, thus contributing to the paucity of the low-inclination orbits in this region. Special provisions, probably related to inefficiencies in the accretional growth of sizable objects, are still needed to explain why only a few low-inclination bodies have been so far detected beyond $\simeq$47 AU.

To appear in: The Astronomical Journal

For preprints, contact `davidn@boulder.swri.edu`

or on the web at `http://arxiv.org/abs/1506.06019`

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The 5:1 Neptune Resonance as Probed by CFEPS: Dynamics and Population

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The Canada-France Ecliptic Plane Survey discovered four trans-Neptunian objects with semimajor axes near the 5:1 resonance, revealing a large and previously undetected intrinsic population. Three of these objects are currently resonant with Neptune, and the fourth is consistent with being an object that escaped the resonance at some point in the past. The non-resonant object may be representative of a detached population that is stable at slightly lower semimajor axes than the 5:1 resonance. We generated clones of these objects by resampling the astrometric uncertainty and examined their behavior over a 4.5 Gyr numerical simulation. The majority of the clones of the three resonant objects (>90%) spend a total of 10^7 years in resonance during their 4.5 Gyr integrations; most clones experience multiple periods of resonance capture. Our dynamical integrations reveal an exchange between the 5:1 resonance, the scattering objects, and other large semimajor axis resonances, especially the 4:1, 6:1, and 7:1 resonances. The multiple capture events and relatively short resonance lifetimes after capture suggest that these objects are captured scattering objects that stick in the 5:1 resonance. These 5:1 resonators may be representative of a temporary population, requiring regular contributions from a source population. We examined the dynamical characteristics (inclination, eccentricity, resonant island, libration amplitude) of the detected objects and their clones in order to provide an empirical model of the orbit structure of the 5:1 resonance. This resonance is dynamically hot and includes primarily symmetric librators. Given our orbit model, the intrinsic population necessary for the detection of these three objects in the 5:1 resonance is 1900^{+3300}_{-1400} (95% confidence) objects with $H_g < 8$ and $e > 0.5$.

Published in: The Astronomical Journal, 149, 202 (2015 June)

Preprints available on the web at `http://arxiv.org/abs/1504.08041`

PAPERS RECENTLY SUBMITTED TO JOURNALS

The Evidence for Slow Migration of Neptune from the Inclination Distribution of Kuiper Belt Objects

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Much of the dynamical structure of the Kuiper belt can be explained if Neptune migrated over several AU, and/or if Neptune was scattered to an eccentric orbit during planetary instability. An outstanding problem with the existing formation models is that the distribution of orbital inclinations they predicted is narrower than the one inferred from observations. Here we perform numerical simulations of Kuiper belt formation starting from an initial state with Neptune at $20 < a_{\rm N,0} < 30$ AU and a dynamically cold outer disk extending from beyond $a_{\rm N,0}$ to 30 AU. Neptune's orbit is migrated into the disk on an e-folding timescale $1 \leq \tau \leq 100$ Myr. A small fraction ($\sim 10^{-3}$) of the disk planetesimals become implanted into the Kuiper belt in the simulations. By analyzing the orbital distribution of the implanted bodies in different cases we find that the inclination constraint implies that $\tau \gtrsim 10$ Myr and $a_{\rm N,0} \lesssim 25$ AU. The models with $\tau < 10$ Myr do not satisfy the inclination constraint, because there is not enough time for various dynamical processes to raise inclinations. The slow migration of Neptune is consistent with other Kuiper belt constraints, and with recently developed models of planetary instability/migration. Neptune's eccentricity and inclination are never large in these models ($e_{\rm N} < 0.1$, $i_{\rm N} < 2°$), as required to avoid excessive orbital excitation in the >40 AU region, where the Cold Classicals presumably formed.

Submitted to: The Astronomical Journal
For preprints, contact `davidn@boulder.swri.edu`
or on the web at `http://arxiv.org/abs/1504.06021`

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Astrometrical Observations of Pluto-Charon system with the Automated Telescopes of Pulkovo Observatory

A.V. Devyatkin[1]**, E.A. Bashakova**[1]**, and V.Yu. Slesarenko**[1]
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The space probe "New Horizons" was launched on 19th of January 2006 in order to study Pluto and its moons. Spacecraft will fly by Pluto as close as 12,500 km in the middle of July 2015 and will get the most detailed images of Pluto and its moon until this moment. At the same time, observation obtained by the ground-based telescopes may also be helpful for the research of such distant system. Thereby, the Laboratory of observational astrometry of Pulkovo Observatory of RAS made a decision to reprocess observations obtained during last decade. More than 350 positional observations of Pluto-Charon system were carried out with the mirror astrograph ZA-320M at Pulkovo and Maksutov telescope MTM-500M near Kislovodsk. These observations were processed by means of software system APEX-II developed in Pulkovo observatory and numerical simulation was performed to calculate the differences between positions of photocenter and barycenter of Pluto-Charon system.

Submitted to: Planetary and Space Science
For preprints, contact `adev@gao.spb.ru`
or on the web at `http://arxiv.org/abs/1504.06199`

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Pluto's Atmosphere from Stellar Occultations in 2012 and 2013

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We analyze two multi-chord stellar occultations by Pluto observed on July 18th, 2012 and May 4th, 2013, and monitored respectively from five and six sites. They provide a total of fifteen light-curves, twelve of them being used for a simultaneous fit that uses a unique temperature profile, assuming a clear (no-haze) and pure N_2 atmosphere, but allowing for a possible pressure variation between the two dates. We find a solution that fits satisfactorily (i.e. within the noise level) all the twelve light-curves, providing atmospheric constraints between ~1,190 km (pressure ~11 μbar) and ~1,450 km (pressure ~0.1 μbar) from Pluto's center. Our main results are: (1) the best-fitting temperature profile shows a stratosphere with strong positive gradient between 1,190 km (at 36 K, 11 μbar) and $r = 1,215$ km (6.0 μbar), where a temperature maximum of 110 K is reached; above it is a mesosphere

with negative thermal gradient of -0.2 K km^{-1} up to ~1,390 km (0.25 μbar), where, the mesosphere connects itself to a more isothermal upper branch around 81 K; (2) the pressure shows a small (6%) but significant increase (6-σ level) between the two dates; (3) without troposphere, Pluto's radius is found to be $R_P = 1,190 \pm 5$ km. Allowing for a troposphere, R_P is constrained to lie between 1,168 and 1,195 km; (4) the currently measured CO abundance is too small to explain the mesospheric negative thermal gradient. Cooling by HCN is possible, but only if this species is largely saturated; Alternative explanations like zonal winds or vertical compositional variations of the atmosphere are unable to explain the observed mesospheric trend.

Submitted to: The Astrophysical Journal
For preprints, contact alexoliveira@on.br
or on the web at http://arxiv.org/abs/1506.08173

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On the Provenance of Pluto's Nitrogen (N_2)

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N_2 is abundant in Pluto's atmosphere and on its surface, but the supply is depleted by prodigious atmospheric escape. We demonstrate that cometary impacts could not have delivered enough N_2 mass to resupply Pluto's atmospheric escape over time; thus Pluto's N_2 is likely endogenous, and therefore was either acquired early in its history or created by chemistry inside/on Pluto. We find that cratering could excavate a considerable amount of N_2 to resupply the atmosphere against escape if the near-surface N_2 reservoir is deep. However, we find that this process likely falls short of that necessary to resupply the atmosphere against escape by at least an order of magnitude. We conclude that either the escape of N_2 from Pluto's atmosphere was on average much lower than the predictions for the current epoch, or that internal activity could be necessary to bring N_2 to the surface and resupply escape losses. Observations made by the New Horizons spacecraft in mid-2015 will yield further constraints on the provenance and evolution of Pluto's surface and atmospheric N_2, and could reveal evidence for past or present internal activity.

Submitted to: The Astrophysical Journal Letters
For preprints, contact ksinger@boulder.swri.edu
or on the web at http://arxiv.org/abs/1506.00913

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Spin-orbit Coupling and Chaotic Rotation for Circumbinary Bodies. Application to the Small Satellites of the Pluto-Charon System

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Circumbinary bodies are objects that orbit around a more massive binary system. Here we show that, contrarily to the classical two-body problem, circumbinary bodies in planar quasi-circular orbits can present stable non-synchronous rotation. Denoting n_b and n the orbital mean motion of the binary and of the circumbinary body, respectively, there is an entirely new family of spin-orbit resonances at the frequencies $n \pm k\nu/2$, where $\nu = n_b - n$, and k is an integer. In addition, when the natural

rotational libration frequency has the same magnitude as ν, the individual resonances overlap and the rotation becomes chaotic. We apply these results to the small satellites in the Pluto-Charon system. We conclude that the rotation of Nix and Styx can be chaotic, and that the rotation of Hydra and Kerberos is stable but not necessarily synchronous.

Submitted to: **Astronomy & Astrophysics**
For preprints, contact `correia@ua.pt`
or on the web at `http://arxiv.org/abs/1506.06733`

OTHER PAPERS OF INTEREST

Formation of Super-Earth Mass Planets at 125–250 AU from a Solar-type Star

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We investigate pathways for the formation of icy super-Earth mass planets orbiting at 125–250 AU around a 1 $M_\odot$ star. An extensive suite of coagulation calculations demonstrates that swarms of 1 cm to 10 m planetesimals can form super-Earth mass planets on time scales of 1–3 Gyr. Collisional damping of $10^{-2} - 10^{2}$ cm particles during oligarchic growth is a highlight of these simulations. In some situations, damping initiates a second runaway growth phase where 1000–3000 km protoplanets grow to super-Earth sizes. Our results establish the initial conditions and physical processes required for *in situ* formation of super-Earth planets at large distances from the host star. For nearby dusty disks in HD 107146, HD 202628, and HD 207129, ongoing super-Earth formation at 80–150 AU could produce gaps and other structures in the debris. In the solar system, forming a putative planet X at $a \leq 300$ AU ($a \geq 1000$ AU) requires a modest (very massive) protosolar nebula.

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Results of Two Multi-chord Stellar Occultations by Dwarf Planet (1) Ceres

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We report the results of two multi-chord stellar occultations by the dwarf planet (1) Ceres that were observed from Brazil on 2010 August 17, and from the USA on 2013 October 25. Four positive detections were obtained for the 2010 occultation, and nine for the 2013 occultation. Elliptical models were adjusted to the observed chords to obtain Ceres' size and shape. Two limb fitting solutions were studied for each event. The first one is a nominal solution with an indeterminate polar aspect angle. The second one was constrained by the pole coordinates as given by Drummond et al.. Assuming a Maclaurin spheroid, we determine an equatorial diameter of 972 ± 6 km and an apparent oblateness of 0.08 ± 0.03 as our best solution. These results are compared to all available size and shape determinations for Ceres made so far, and shall be confirmed by the NASA's *Dawn* space mission.

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