PECULIAR COMETS EJECTED EARLY IN SOLAR SYSTEM FORMATION. S.E. Anderson[1], J.-M. Petit[1], B. Noyelles[1], O. Mousis[2], and P.Rousselot[1], [1] Institut UTINAM UMR 6213, CNRS, Univ. Bourgogne Franche-Comté, OSU THETA, BP 1615, 25010 Besançon Cedex, France (sarah.anderson@univ-fcomte.fr), [2]Aix Marseille Univ, CNRS, CNES, LAM, Marseille, France.

Introduction: Radio observations of the long period comet C/2016 R2 (PanSTARRS), hereafter R2, revealed that it was a CO-rich comet remarkably depleted in water [1]. Further, the spectrum was dominated by bands of CO^+ as well as N_2^+, the latter of which never being seen in such abundance in comets before [2][3]. This CO and N_2-rich and water-poor composition, along with none of the usual neutrals seen in most cometary spectra, makes R2 a unique and intriguing specimen. Understanding the dynamical history of this comet is thus of essential importance to understanding the timeline of planetesimal formation in our solar system. However, tracking such a small object backward with any degree of certainty is made impossible by the inherent chaotic nature of its motion due to frequent close encounters with the gas giants. Alternative measures must be employed in order to determine where this unique comet originated from.

Two studies have independently estimated the possible origin of this comet from building blocks formed in a peculiar region in the protoplanetary disk, near the ice line of CO and N_2. By evaluating the radial transport of volatiles in the Protoplanetary Disk (PPD), Mousis (2021) [4] found that R2's peculiar N_2/CO ratio could be replicated by agglomeration from particles near the N_2 and CO icelines, i.e. within the 10-15 au region. Meanwhile, the CO/H_2O ratio would remain deeply depleted inward of the CO iceline (see Figure 1). Similarly, Price (2021) [5] model the effect of drifting solid material in the PPD and find that the ideal location for the objects to form is beyond CO iceline. However, this would indicate that more CO rich comets should exist than have previously been observed.

Methods: Here we explore the potential fates of comets formed from these building blocks using a numerical simulation of early solar system formation and tracking the dynamics of these objects in the Jumping Neptune scenario Nesvorny (2015) [6]. We start with five planets: Jupiter, Saturn, and three ice giants, as described by Deienno et al (2017) [7]. The planetary evolutions are selected to meet criteria of similarity with the solar system today, among which having four planets and Jupiter and Saturn having suffered a rapid separation of their orbits due to an instability while crossing a mean motion resonance.

We fill the disk between 4 au to avoid the inner solar system, and 50 au with massless comet facsimiles or 'clones'. We then use a modified SWIFT numerical integrator which uses a pre-recorded evolution of the giant planets [8] and evolve our system over 100 Myr.

Our simulations count a clone as lost if it reaches beyond 10,000 au as we don't have the ability to estimate the effects of the galactic tidal forces. We will also count a clone as ejected if the eccentricity exceeds 1—while beyond the influence of the giant planets—as this is when it is deemed hyperbolic and assumed to have left the system. Realistically, this clone could equally be integrated into the Oort cloud. Finally, if a clone moves under 0.5 au from the sun, it is also removed from the integration.

We do this for 5 different initial conditions of the planets in the disk. For each initial condition we generate and run 1000 clones 50 times, for a total of 50000 clones per set.

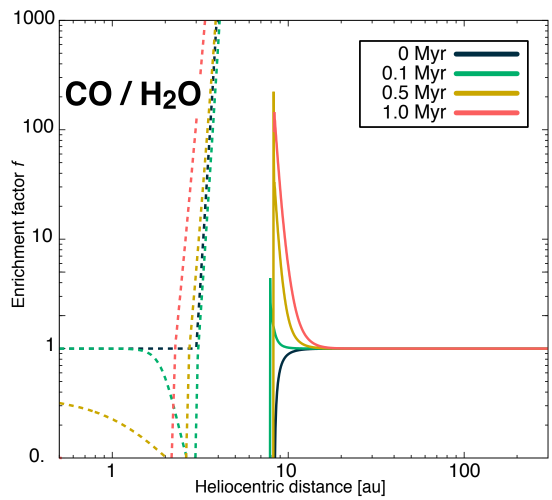

Fig.1: *Radial profiles of the CO/H_2O ratio relative to its initial abundance (defined by the enrichment factor f) calculated as a function of time in the protosolar nebula for a viscosity parameters* $\alpha = 10^{-4}$*. Dashed and solid lines correspond to vapor and solid phases, respectively. See [4] for details.*

Results: Within the first 5 Myr , over a third of all clones are 'ejected' from the solar system. This number rises to nearly half after 10 Myr and to over half after 15 Myr. The major loss of clones occurs before Jumping Neptune at ~12 Myr. After this time, the area around the giant planets is entirely cleared. These are shown in figure 2.

If we examine the region of clones initialized between 10 – 20 au, we find that half the clones are already ejected by 5 Myr, with two thirds of clones ejected after 15 Myr. If we narrow that region further to 10 – 15 au as suggested by [4], we find that two thirds of clones formed in this region are ejected in the first 5 Myr and three quarters after 15 Myr.

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These results are coherent with our current understanding of the chronology of Oort cloud formation [9].

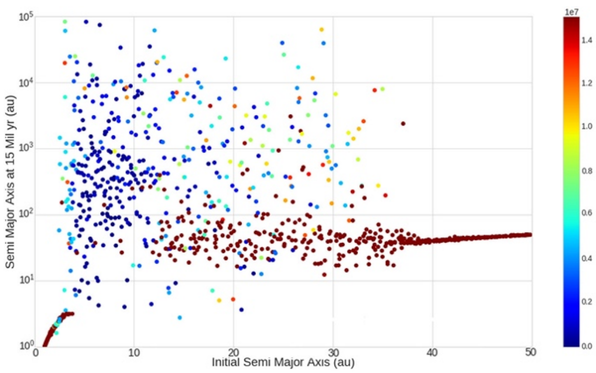

Fig 2: *Semimajor axis of each clone after 20 Myr as a function of their initial semimajor axis. The colorbar represents when the clone was 'ejected', with blue being within the first Myr, and dark red being those which 'remain' within the system. These results are shown with clones generated between 1 and 50 au .*

Conclusion: We find that the majority of objects formed between Saturn and the N_2 iceline are ejected early in the simulation, so that even by the time the Jumping Neptune scenario happens, the clones are already gone.

This could potentially explain the lack of comets rich in N_2 and depleted in water: they were formed in a very narrow region, and that region was unstable due to Jupiter and Saturn. Another factor would be the rapidity at which this reservoir depleted. This would similarly explain the lack of CO rich comets: while they would form near their iceline, this area empties rapidly due to the influence of giant planets.

Further numerical simulations are required in order to investigate the behavior of these comets beyond the 10,000 au cutoff. If these comets are indeed ejected from the solar system, it would be a likely explanation for the composition of interstellar visitors, such as interstellar comet 2I/Borisov, which was measured to have CO/H_2O between 35%-173% ([10];[11]), significantly higher than the average cometary values for the Solar System, though not as high as comet R2.

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