EVOLUTION OF BINARY PLANETESIMALS DUE TO GAS DRAG IN THE SOLAR NEBULA. William B. McKinnon[1], D.P. Hamilton[2], W.M. Grundy[3], J.T. Keane[4], D. Nesvorny[5], C.B. Olkin[5], S.B. Porter[5], K.N. Singer[5], J.R. Spencer[5], S.A. Stern[5], O.M. Umurhan[6], H.A. Weaver[7], and the *New Horizons* Science Team; [1]Dept. Earth and Planetary Sci. and McDonnell Center for the Space Sci., Washington University in St. Louis, Saint Louis, MO 63130 (mckinnon@wustl.edu), [2]Dept. Astronomy, Univ. Maryland, College Park, MD 20742, [3]Lowell Obs., Flagstaff, AZ 86001, [4]GPS, Caltech, Pasadena CA 91125, [5]SwRI, Boulder, CO 80302, [6]NASA Ames Res. Center, Moffett Field, CA 94035, [7]JHUAPL, Laurel, MD 20723.

Introduction: The apparent gentle merger of the two lobes of the cold classical Kuiper belt object (KBO) 486958 Arrokoth (formerly 2014 MU_{69}), as revealed by *New Horizons* [1,2], prompts consideration of the physical mechanism(s) that might have driven mergers of originally co-orbiting binaries (which are known to be common in the Kuiper belt today [3]). In [4] several mechanisms were examined: tides, collisions, Kozai-Lidov cycling, asymmetric radiation effects (YORP and BYORP), and gas drag. Here we examine the case for gas drag, both as it might have affected Arrokoth and more generally.

Gas Drag in the Kuiper Belt: The leading mechanism for binary formation in the Kuiper belt is gravitational instability (GI) of overdense particle (or "pebble") swarms following the streaming or some other instability in the protosolar nebula [5,6]. Within the collapsing pebble cloud itself, [5] estimate that the mean collision time is shorter than the gas-drag stopping time. Hence binary formation and dynamics during GI are dominated by collisions and dynamical friction, not intracloud gas dynamics. Once the cloud remnant clears out, however, the binary is subject to gas drag forces for as long as the gas in the protosolar nebula at the binary's heliocentric distance persists.

The evolution of binaries in a gaseous protoplanetary disk was first considered in detail by [7], who focused on the possibility of differential wind shear causing binaries to become unbound, and secondarily on the possibility that gas drag could cause binary inspiral and merger. The former is not an issue for the relatively massive lobes of Arrokoth, and we derive a new and different result than [7] for the latter.

Classically, the momentum flux imparted by an ambient gas to a moving object yields a stopping time of $t_{stop} \sim \rho R/(C_D \rho_{gas} \upsilon)$, where R is the effective radius of the object, ρ and C_D are its bulk density and drag coefficient, respectively, and ρ_{gas} is the ambient gas density —a well-known astrophysical result that goes back at least to Whipple [8]. Adopting a characteristic midplane ρ_{gas} at 44.2 AU of 1×10^{-10} kg m^{-3} from [9] and an initial semimajor axis for Arrokoth of 100 km, and assuming a drag coefficient C_D of ~unity appropriate to fully turbulent drag (see below), yields an orbital speed $\upsilon = \upsilon_{orb}$ ~1 m/s and stopping times of ~500 Myr for ρ = 500 kg m^{-3} and an average R = 7 km (with gas drag acting on each lobe). Because this is much longer than any plausible lifetime for the protosolar nebula, it might seem that ambient gas had little effect on Arrokoth's later evolution.

However, the gas drag environment experienced by Arrokoth would have been more complex than this simple picture. The nebular gas at Arrokoth's distance from the Sun would have been moving at sub-Keplerian speeds ($r\Omega$) owing to the pressure gradient in the nebula [7,8,10]:

$$\Omega^2 r = \Omega_K^2 r + \frac{1}{\rho}\frac{\partial P}{\partial r} \quad , \tag{1}$$

where Ω_K is the Keplerian angular velocity, P is the gas pressure, and r is the heliocentric distance. Because the binary is massive enough that it itself orbits the Sun at Keplerian speed, it will feel a headwind (at velocity $\upsilon_{wind} = r(\Omega_K - \Omega)$), which we estimate from [9] to be ~50 m/s, about 1% of the Keplerian speed. It is this gas velocity that determines the drag regime for Arrokoth (and for many binaries), irrespective of the binary's orientation, and couples to the slower velocity of the co-orbiting binary. As the binary pinwheels in this nebular wind (Fig. 1), each of its lobes will alternately feel accelerating and decelerating torques; time averaged over both the binary's mutual and heliocentric orbital periods, the difference will be a cross term proportional to $\upsilon_{orb}\upsilon_{wind}$, resulting in a modified stopping time (e-folding time of the binary's angular momentum)

$$t_{stop,wind} \sim \frac{\rho R}{C_D \rho_{gas} \upsilon_{wind}} \quad , \tag{2}$$

and where the high obliquity of (e.g.) Arrokoth has been taken into account.

The kinematic viscosity (η) of protosolar nebula gas, for the above midplane conditions, is ~10^5 m^2/s. That is, the mean free path in the nebular gas $\lambda = 1/n\sigma_H$, where σ_H is the collisional cross section of H_2 and n the number density. For the midplane density above we find $\lambda \sim 0.17$ km, which puts Arrokoth's gas interactions into the fluid (Stokes-like) regime. The kinematic viscosity is then $\lambda \times$ sound speed, which for cold, 30 K nebular gas [9,11] is 7×10^4 m^2 s^{-1} independent of ρ_g. This in turn implies Reynolds numbers $Re \equiv 2R\upsilon_{wind}/\eta$ ~ 15 for Arrokoth in particular. This puts Arrokoth into the intermediate drag regime [10,12], with corresponding C_D values of $24Re^{-0.6} \sim$ 5-10 for its two, non-spherical lobes. Combined with the wind-speed dependence in the time-averaged torque, the gas-drag stopping time (a measure of the binary merger time scale) decreases by a factor of ~250-500, to times of order ~1–2 Myr for Arrokoth. Such time scales are commensurate with the short lifetimes of protoplanetary gas disks [e.g., 13,14]. Total, upper limit merger times, if Arrokoth's original orbit extended to its outer Hill sphere (~10^4 km), would have been a few times longer.

The nebular density profile [9] was adopted above because it fully corresponds to the initial compact giant planet configuration and outer planetestimal disk thought likely to represent our nascent solar system [e.g., 15]. As such it was designed to represent the protoplanetary nebula at the time of planetesimal formation. It also assumes that the nebula (gas or solids) does not end abruptly at ~30 AU, but simply declines in planetesimal surface density to satisfy the damped migration constraint for Neptune [16]. In contrast, if the gas nebula was highly attenuated in the CCKB region, gas-drag binary hardening would have been ineffective. But because the characteristics of Arrokoth argue for planetesimal formation via the streaming or a related collective instability, there must have been sufficient gas and, at least locally or intermittently, sufficiently high solid/gas ratios for such instabilities to occur.

Conclusion: Even considering the variations owing to alternative protosolar nebula models [e.g., 12,17], this somewhat startling result implies that headwind-coupled gas drag may be the dominant mechanism that drove the merger of small Kuiper belt binaries such as Arrokoth. In the intermediate-*Re* drag regime, the merger time scales as $\rho R^{1.6}$, so smaller (i.e., cometary) binaries similar to 67P in scale should have evolved even more rapidly to become contact binaries. Nor do the effects of gas drag cease once the contact binary forms, though the geometric details of the drag interaction become complicated. Furthermore, low-inclination binaries should shrink faster than high-inclination binaries (by a factor of ~π/2), all other things being equal, because the headwind is always edge-on to their mutual orbits. If so, we predict that for a given heliocentric distance, the physical sizes of low-inclination contact binaries could extend to larger scales than the sizes reached by high-inclination ones; there may also be a complementary bias favoring more distant co-orbiting binaries at high inclinations. Ongoing and future surveys of KBOs should thus provide additional constraints on the role and timing of gas drag (and collective instabilities) in planetesimal formation.

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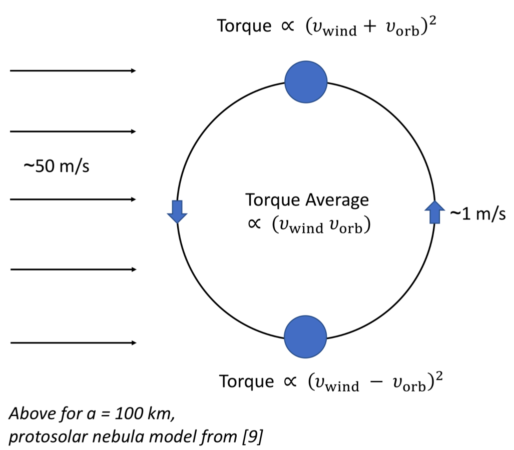

$$t_{\rm stop,wind} \approx \frac{\pi^2 \rho R}{6 C_{\rm D} \rho_{\rm gas} v_{wind}} \ln \sqrt{a_{\rm i}/a_{\rm f}}$$

$$\sim \frac{\rho R}{C_{\rm D} \rho_{\rm gas} v_{wind}}$$

~ 1–2 Myr for Arrokoth

Gas drag is surprisingly effective at hardening CCKB binaries (if not too large)

Figure 1. Illustration of protosolar nebula headwind interaction with a co-orbiting equal mass binary. The averaged torque is proportional to the product of the lobe orbital velocity and the differential velocity between the nebular gas and the binary's center-of-mass about the Sun.