29P/Schwassmann-Wachmann 1 : An Excellent Nearby Laboratory for Studying Amorphous -> Crystalline Water Ice Conversion in Centaurs and Comets

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Introduction. As noted in [1], Centaur 29P/Schwassmann Wachmann 1 is a relatively large (~32 km radius, [2-3]) icy planetesimal residing in a nearly circular orbit just beyond the orbit of Jupiter. It is well known for its unusually high level of CO production and dust emission activity (but not conspicuously for any significant H_2O emission activity) and frequent outbursts [4-9]. Dynamically, Centaurs are an unstable transitional population and they represent the middle state between the long-lived reservoir of icy Kuiper Belt Objects (KBOs) in the outer solar system and the quickly evolving Short Period comet (SP) population in the inner solar system [10-12]. SW1 currently resides in a 'Gateway' orbit: a collection of dynamical orbits that facilitate dynamical migration between these two populations [13-15]. [13] showed that SW1's low-eccentricity orbit just exterior to Jupiter is typical for Centaurs transitioning to Jupiter family comet (JFC) orbits and is very likely to undergo this transition within the next ~10 Kyr.

SW1 is an Usually Large Centaur With Implications for Its Current Behavior. SW1 is special because it is very large compared to the typical "Gateway" Centaur/Comet. [13] estimate that only ~4% of the objects reaching the Gateway are this size or larger. Its volume reserves of amorphous water ice (AWI) are thus large enough versus the input solar energy flux that $\tau_{thermal}$, the time it takes to convert all its AWI -> CWI (crystalline water ice), the proposed process driving emission activity for Centaurs [16-18] occurring inside 10 au, is 60 - 100 Myr. This is much longer than the ~10 Myr it typically takes a KBO to travel from the outer solar system to 6 au [13, 19-22] and the few Myr the KBO resides inside 10 au (Saturn's orbit), meaning that it has not yet exhausted the supply of any AWI it may have had while residing in the Kuiper Belt region, and it likely ***still*** undergoing AWI to CWI conversion today [1].

Modeling. To prove that SW1 is still converting AWI to CWI, we present the modeling treatment of [23], which follows the changing internal structure of an icy SW1 nucleus reacting to solar heating, starting with a composition of CO-laden amorphous ice and rock, until the ice crystallizes throughout the body. The code solves coupled differential equations for energy and mass flows simultaneously, while allowing for internal heat sources like the heat of phase change and bodies consisting of many different ice species, each with their own effective heat of sublimation and crystallization. Energy can diffuse into the interior via solid state conduction, radiation, and/or gas advection. [19, 24-25].

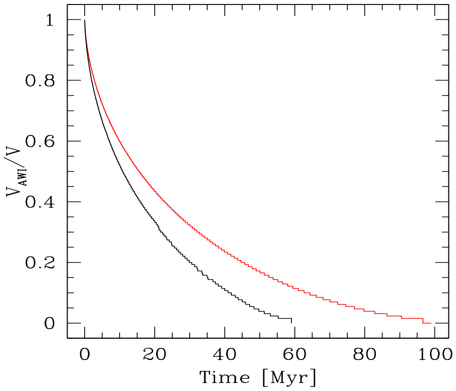

Figure 1 – Model results for AWI depletion via CWI conversion for SW1-like bodies of bulk chondritic abundance and 1:1 ice:rock ratio. In each figure the two curves are the results for assuming two different enthalpies for the AWI -> CWI transition: red for $\Delta H_{AWI\ conversion} = 0$ energy released, which produces the slowest transformation rate, black for the faster $\Delta H_{AWI\ conversion} = -45$ kJ of heat released per kg of CWI produced. (***Top***) Fraction of AWI left after a given time for a spherical 32 km radius SW1-like body. After 10 Myr, only ~35% of the AWI in the ΔH= 0 kJ/kg and 50% of the AWI in the ΔH= -45 kJ/kg released case has transformed. (***Bottom***) Time for depletion of all AWI throughout the entire body. The ΔH = 0 curve follows an approximate $R_{nuc}^{1.65}$ law & the ΔH = -45 kJ/kg curve an approximate $R_{nuc}^{1.61}$ law.

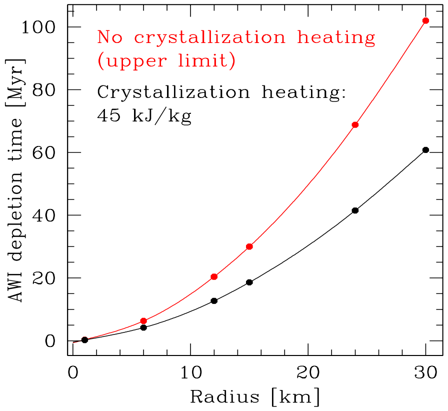

Table 1 – Prialnik Model Parameters

Parameter	Value
Ice heat capacity	7.5×10^4 T + 9.0×10^5 erg g^{-1} K^{-1}
Dust heat capacity	1.3×10^7 erg g^{-1} K^{-1}
AWI thermal conductivity	2.35×10^2T + 2.82×10^3 erg cm^{-1} s^{-1} K^{-1}
CWI thermal conductivity	5.67×10^7/T erg cm^{-1} s^{-1} K^{-1}
Dust thermal conductivity	2×10^4 erg cm^{-1} s^{-1} K^{-1}
Crystallization rate	1.05×10^{13} $e^{-5370/T}$ s^{-1}
Latent heat of ice sublimation	2.8×10^{10} erg g^{-1}
Dust specific density	3.25 g cm^{-3}
Average pore size	0.1 cm

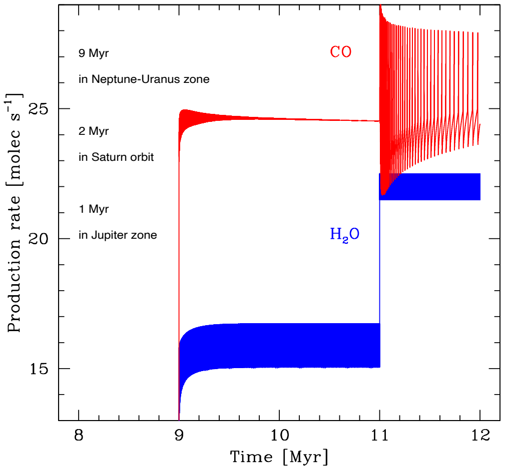

Figure 2. - Relative CO and H_2O gas production rates for the Prialnik model of Figure 1, assuming a 32 km radius, 5% CO/H_2O, 1:1 Ice/Rock (by mass) body that has spent 4.56 Gyr in the Kuiper Belt, then 9 Myr in the Neptune- Uranus region, 2 Myr near Saturn, and finally the last 1 Myr near Jupiter at 6 au. Other dynamical trajectories are possible, for example a body that has slowly but monotonically inspiralled from ~40 au to ~6 au rather than moved stochastically, and they produce similar $Q_{CO}/Q_{H2O} > 10^3$ production ratios. Note that the predicted gas production rates oscillate in time, suggesting a thermophysical mechanism for producing SW1's observed outbursts.

CO and "Dust" Emission But No CO_2 Emission. The scenario of ongoing AWI crystallization driving SW1's activity is consistent with SW1 producing large amounts of gaseous CO into its coma as removal of excess molecular "impurities" over and above the amount storable in a CWI hydrate lattice, ≦ 20% of the total H_2O ice volume occurs [26-27], without large-scale bulk mass water ice removal. The ~-18% volume change upon CWI conversion could also drive contractual geomorphological changes like faulting, sinkholes, and landslides. Such changes, if violent enough, could drive "dust" (= bulk rocky material + refractory organics + crystalline water ice) emission activity [28-31], along with CO gas entrainment [32] and buried pockets of high pressure CO gas [33]. The lack of any observed CO_2 emission, typical of comets, is explained by the high sticking probability of CO_2 onto water ice up to ~105 K [34], so that we can expect the emitted "dust" to be rich in adsorbed CO_2 as well.

Implications. These arguments have a number of important, testable predictions [1], including: that to date SW1 has only converted between 50 to 65% of its nuclear AWI to CWI; that volume changes upon AWI conversion could have caused subsidence and cave-ins, but not significant mass wasting on SW1; that when SW1 transits into the inner system within the next ~1 Myr, it will be a very different kind of short period (SP) comet; that SW1's coma should contain abundant amounts of CWI-rich "dust" particles; and the quick release on Myr timescales of CO from AWI conversion for any few km-scale scattered disk TNO transiting into the inner system.

Tests. A number of remote sensing and in situ spacecraft investigations are immediately suggested by these arguments: (i) Further refining of [16-17]'s Centaur activity vs heliocentric distance surveys should be done taking into account Centaur size, as smaller Centaurs will convert their AWI more quickly and become inactive sooner, even those with q < 10 au. (ii) Surface blow-out craters and sinkholes (like the ones seen on young SP comet 81P/Wild 2, [35-36]) should be searched for, due to pockets of CO gas buried beneath a lag layer requiring the buildup of significant over-pressure before being released in a stochastic outburst. (iii) Insignificant whole-body mass-wasting should maintain a relatively old surface geomorphology elsewhere. (iv) CO released from AWI should be co-mingled with other highly volatile minor gas species, like CH4, and their release could be searched for by an *in situ* gas analyzer. (v) Coma grains surrounding SW1 should still contain much of their CWI and CO_2, with the highest CWI content being found in the youngest grains nearest the nucleus.

References. **[1]** Lisse et al. 2022 **[2]** Schambeau et al. 2021, PSJ 2, id.126 **[3]** Bockelee-Morvan et al. 2022, A&A 664, A95 **[4]** Senay & Jewitt 1994, Nature 371, 229 **[5]** Gunnarsson et al. 2008, A&A 484, 537 **[6]** Trigo-Rodriguez 2008, A&A 485, 599 **[7]** Trigo-Rodriguez 2010, MNRAS 409, 1682 **[8]** Hosek et al. 2013, Astron. J 145, 122 **[9]** Wierzchos & Womack 2020, Astron J. 159, 136. **[10]** Dones et al. 2015, Space Science Reviews, 197, 191 **[11]** Peixinho et al. 2020, in The Trans-Neptunian Solar System, 307 **[12]** Fraser et al. 2023, Comets III (under review) **[13]** Sarid et al. 2019, Astrophys J Lett 883, id. L25 **[14]** Steckloff et al. 2020, Astrophys J Lett 904, L20 **[15]** Seligman et al. 2021, PSJ 2, 234 **[16]** Prialnik et al. 1995, MNRAS 276, 1148 **[17]** Jewitt 2009, Astron J 137, 4296 **[18]** Li et al. 2020, Astron J 159, Issue 5, id.209 **[19]** Volk & Malhotra 2008, Astrophys J 687, 714 **[20]** Prialnik & Rosenberg 2009 **[21]** Di Sisto & Rossignoli 2020, Celestial Mech & Dynamical Astron 132, id.36 **[22]** Gkotsinas et al. 2022, Astrophys J 928, 43 **[23]** Prialnik 2021, AAS/DPS Poster Program Number: 307.10 **[24]** Prialnik et al. 2004, Comets II, 359 **[25]** Prialnik et al. 2008, Space Sci Rev 138, 147 **[26]** Schmitt et al. 1989, ESA SP-302, 65 **[27]** Jenniskens & Blake 1996, Astrophys. J. 473, 1104 **[28]** Belton et al. 2008, Icarus 198, 189 **[29]** Belton et al. 2011, EPSC-DPS Joint Meeting 2011, 1025 **[30]** Steckloff et al. 2016, Icarus 272, 60 **[31]** Steckloff & Samarasinha 2018, Icarus 312, 172 **[32]** Finson & Probsten 1968, Astrophys J 154, 327 **[33]** Yelle et al. 2004, Icarus 167, 30 **[34]** He et al. 2016, Astrophys. J 823, 56 **[35]** Brownlee et al. 2004, Science 304, 1764 **[36]** Cheng et al. 2013, Icarus 222, 808