Final Report DE-SC0020079

Ice Dusty Plasma

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The NSF/DOE funding described in this final report was for constructing a substantial upgrade that would enable operation at variable and much lower cryogenic temperatures than was available in a previous experiment that operated from 2013 to 2019. Components for the upgraded experiment were designed and ordered from August to December 2019 and assembly began in early 2020. However, COVID-19 halted all lab work for much of 2020 and then when lab work resumed, numerous restrictions on lab access and in-lab time further impeded progress. Because of these delays, first plasma was obtained in late 2021 and a normal work pace resumed only in mid-2022. A no-cost extension was requested because the COVID-19 delays prevented work from being done at the anticipated rate.

Constructing a water-ice experiment was a significant gamble because the parameter regime differs substantially from conventional laboratory plasmas and injecting water vapor into a plasma goes very much against convention as one normally goes to great lengths to avoid water vapor. This experiment opens a new frontier, namely the study of how charged ice grains form, grow, and interact with a plasma environment. The just-completed upgrade was a further gamble because it combines technology never previously used together (cryocoolers, plasma, and ice).

The new experiment was designed by PI Paul Bellan and assembly/testing was done by graduate student Andre Nicolov under the supervision of Paul Bellan.

Undergraduate Geoff Pomraning worked on the dusty plasma on a novel density diagnostic and an ice grain imaging diagnostic. Together with a high school teacher, Geoff and P. I. Paul Bellan ran a high school student outreach program during the summers of 2021 and 2022. In this 6 week program a select group of high school students built and used a Gerdien condenser. Three students participated in 2021 and four in 2022; most were from under-represented minorities.

Water is not only important on Earth, but also in many astrophysical and space contexts. As an important example, new stars have associated accretion disks that evolve into protoplanetary disks, the precursors of planets — water in the colder parts of a protoplanetary disk is in the form of ice dust which likely becomes the water on Earth-like planets. As another example, Saturn's diffuse rings are composed of ice dust in the presence of plasma. Comet tails also contain ice dust in a plasma environment.

A common feature of these contexts is that they are cold and involve weakly-ionized plasma. Full ionization would require a temperature exceeding tens of thousands of degrees whereas these contexts have gas temperatures so low that neutral atoms and molecules can coexist with charged particles. The weak ionization results from X-rays, cosmic rays, or UV radiation impinging on neutral gas. The temperature in much of the universe is below 150 K in which case it is not unusual to have a mix of water molecules, water ice, and weakly-ionized plasma. Noctilucent clouds are a terrestrial phenomenon with similar properties. These clouds, located at a surprisingly precise altitude of 85±5 km consist of nanometer-sized water ice grains in a weakly-ionized <150 K background gas.

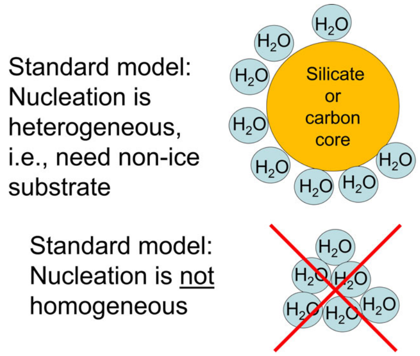

Figure 1: Heterogeneous nucleation (top) versus homogeneous nucleation (bottom)

As sketched in Fig. 1, there are two ways that water molecules can in principle nucleate to form *liquid water drops*: (i) heterogeneous nucleation (rocky substrate) and (ii) homogeneous nucleation (no substrate). However, according to standard model, heterogeneous nucleation dominates homogeneous nucleation by orders of magnitude. Standard models of *ice grain* formation similarly assume dominance of heterogenous nucleation over homogeneous nucleation. Furthermore, standard models of astrophysical dust formation do not consider that plasma could have an influence.

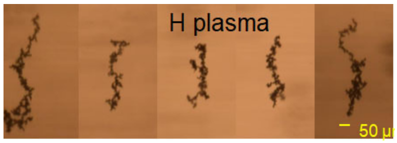

Figure 2: Ice dust in Caltech H plasma, from Chai and Bellan ApJ 2015

Electrical charging of astrophysical dust has occasionally been considered but to the best of the author's knowledge, all models of astrophysical ice dust assume ice dust nucleation is heterogeneous, ignore ice dust charging, and ignore effects of a plasma environment. In stark contradiction to these established models, laboratory experiments by showed that water ice dust nucleates homogeneously in the presence of a weakly-ionized plasma; i.e., the ice nucleates without a non-ice substrate. The reason why plasma promotes rapid homogeneous nucleation of ice dust in these laboratory experiments has been a mystery. Solving this mystery would have enormous ramifications for understanding how ice forms in astrophysical situations because these situations typically have weakly-ionized plasma with parameters not extremely different from these lab plasmas.

The laboratory experiments showed no evidence of silicates or carbon as these experiments were done in clean vacuum chambers with no source of silicates or carbon. Motivated by the mystery of how weakly-ionized plasma enables homogeneous nucleation, PI Bellan recently developed a hypothesis for how plasma-instigated homogeneous nucleation would work (see list of papers below).

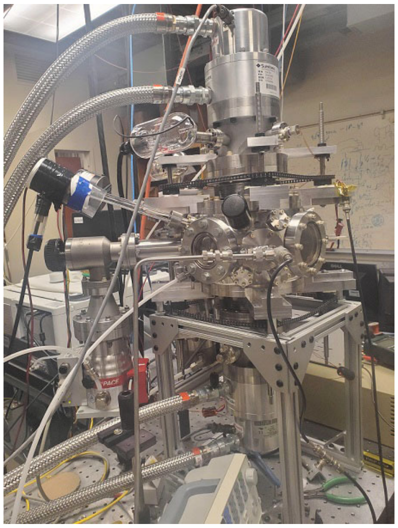

Figure 3: Photo of new experiment showing cryo-coolers at top/bottom and chain drives for electrode adjustment, details in EquipmentAppendix

The 2013-2018 Caltech experiment had an rf-produced weakly-ionized plasma where the background gas was cooled by having the rf electrodes in thermal contact with liquid nitrogen baths. When water vapor was injected into this weakly-ionized plasma immersed in a cryogenically-cooled background gas, water ice grains spontaneously formed. There was independent control of the water vapor and the background gas pressures. Gases H, He, Ne, Ar, Kr were used and water, methanol, acetone vapor were separately injected to form their respective types of ice. Nominal parameters were: $n_e \sim 10^8 - 10^9$ cm^{-3}, $T_i = 0.01$ eV, $T_e = 2$ eV, 50 - 1000 mT background gas pressure, 10^{-6} fractional ionization, water vapor pressure 1% - 10% that of background gas, and a few watts of 13.56 MHz rf power. Non-spherical morphology was observed to be dominant at low background gas pressures and when the background gas species had low mass (e.g., H). In these regimes the dust grains were slightly dendritic spindles and, as shown in Fig.2, attained lengths as great as 700 μm.

Another important result was that the ice dust grains did not follow an r^{-p} size distribution as is typically assumed in the astrophysics literature. Instead, the laboratory-produced ice dust grains were approximately mono-disperse with dimensions determined by ambient plasma conditions. The grains grew quickly and reached full size in one to two minutes after injection of the water vapor into the plasma. The ice dust grains exhibited behavior similar to other dusty plasmas such as lattice formation and vortex motion. In regimes where the ice gains were slightly dendritic spindles, they often self-aligned to be both parallel to each other and equally spaced. There was evidence of dust waves in certain regimes.

Construction of the substantially upgraded dusty plasma experiment began in 2019. Figure 3 shows a photo of this device. The new experiment achieved first plasma in late 2021 and attained reliable production of ice dusty plasmas in mid-2022. The main differences between the new device and the 2013-2018 device are that the new device uses cryocoolers rather than LN_2 Dewars and has a larger vacuum chamber with many more ports. The cryocoolers use a liquid helium refrigerator system as in a cryopump and enable operation at much lower temperatures than could be achieved by the previously used LN_2 cooling. Furthermore, the temperature is controlled by a feedback system that enables exploring how various aspects of ice dust behavior depend on temperature.

Three theoretical papers were published and are:

- Nicolov, André;Bellan, Paul M. (2023) Modeling the energetic tail of a dusty plasma's electron energy distribution and its effect on dust grain charge and behavior, Physics of Plasmas; Vol. 30; No. 8; pp. 083704 DOI 10.1063/5.0145209
- Bellan, Paul M. (2022) Mechanism for the Efficient Homogeneous Nucleation of Ice in a Weakly Ionized, Ultracold Plasma, Astrophysical Journal; Vol. 936; No. 1; pp. Art. No. 52 DOI 10.3847/1538-4357/ac85bd
- Bellan, P. M. (2020) Why Interstellar Ice Dust Grains Should Be Elongated, Astrophysical Journal; Vol. 905; No. 2; pp. Art. No. 96 DOI 10.3847/1538-4357/abc55b

A paper reporting experimental measurements of regimes where either amorphous or crystalline ice grains are produced is under review. This paper is titled "Phase, morphology, and formation of water-ice grains in a cryogenic laboratory plasma" and the authors are A. Nicolov, M. Gudipati, and P. M. Bellan.

The figures on the following pages provide an overview of the design and some initial results of this experiment.

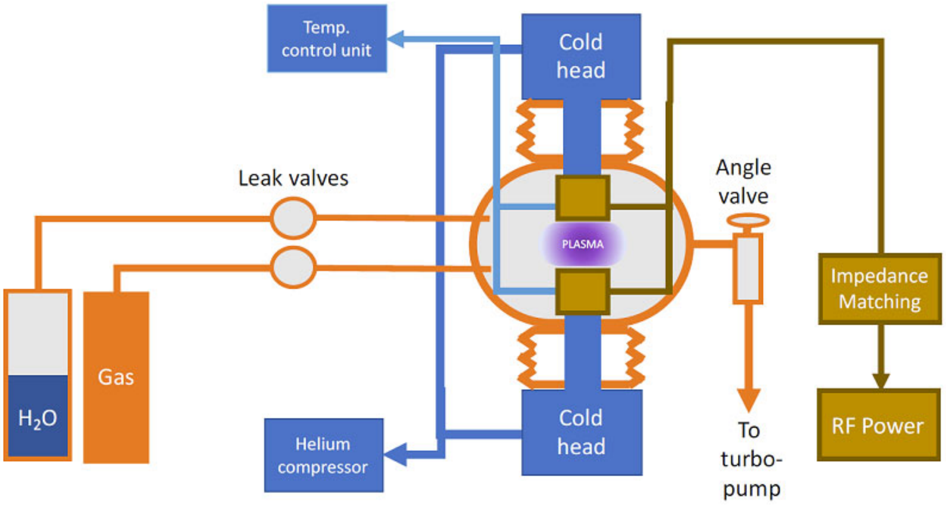

Figure 4: Schematic of new experimental facility. Top and bottom electrodes are cooled to cryogenic temperatures via cryocoolers connected to a helium compressor. Background gas and water vapor are introduced to the vacuum chamber by leak valves. The plasma is powered by a 13.56 MHz RF generator connected to the electrodes via an impedance matching network.

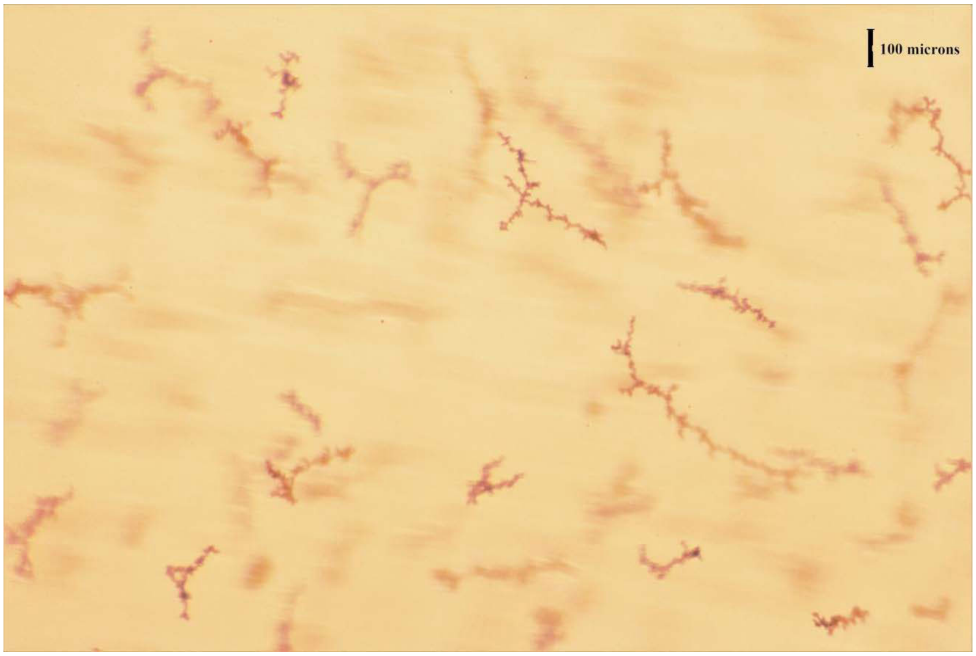

Figure 5: Ice dust gains in hydrogen background gas in new experimental facility photographed in February 2023.

Figure 6: Ice grains in hydrgen plasma, 800 mT pressure, February 6, 2023, regular lens.

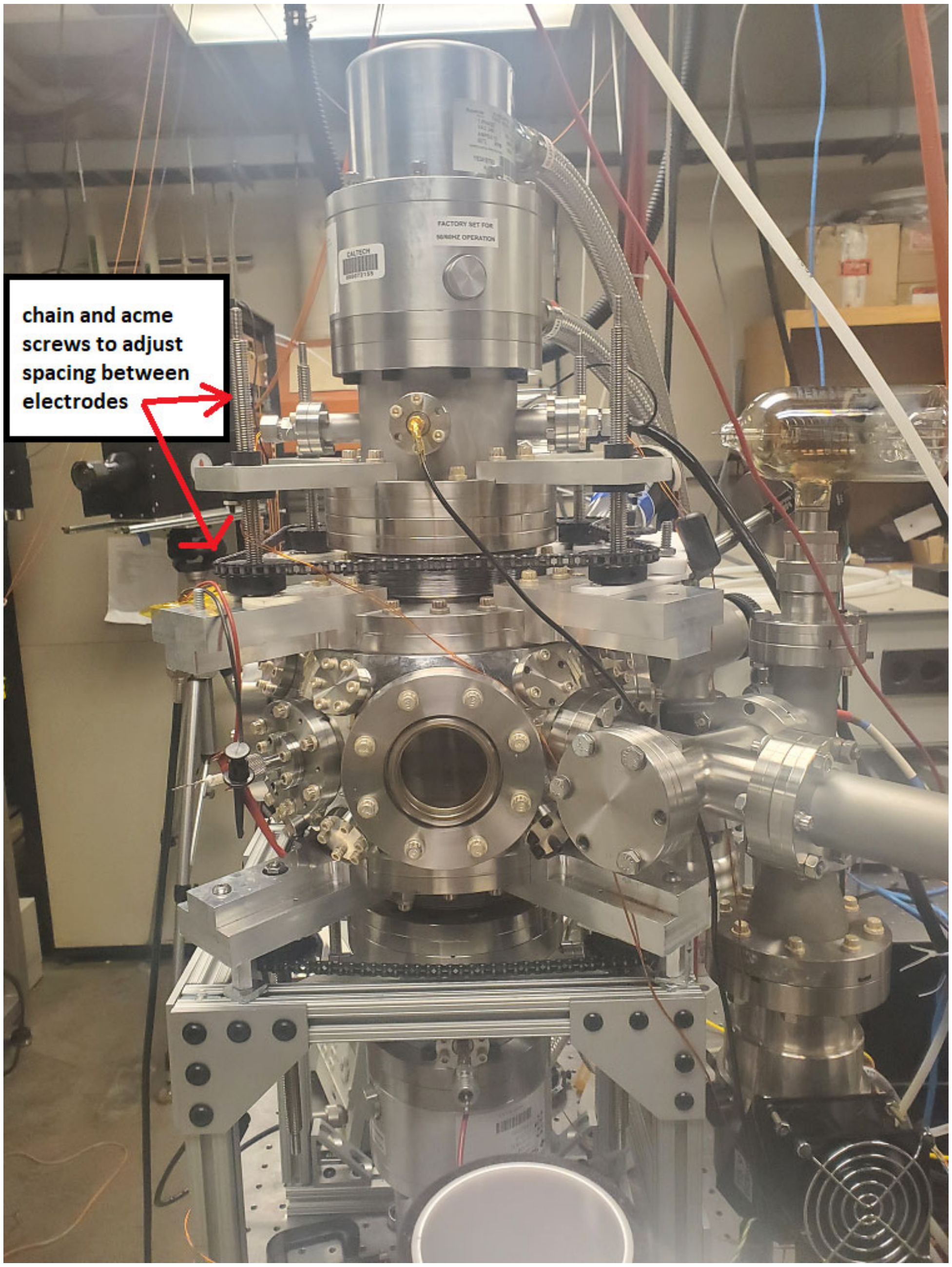

Figure 7: Photo showing chain-driven acme screws that enable adjustment of distance between electrodes.

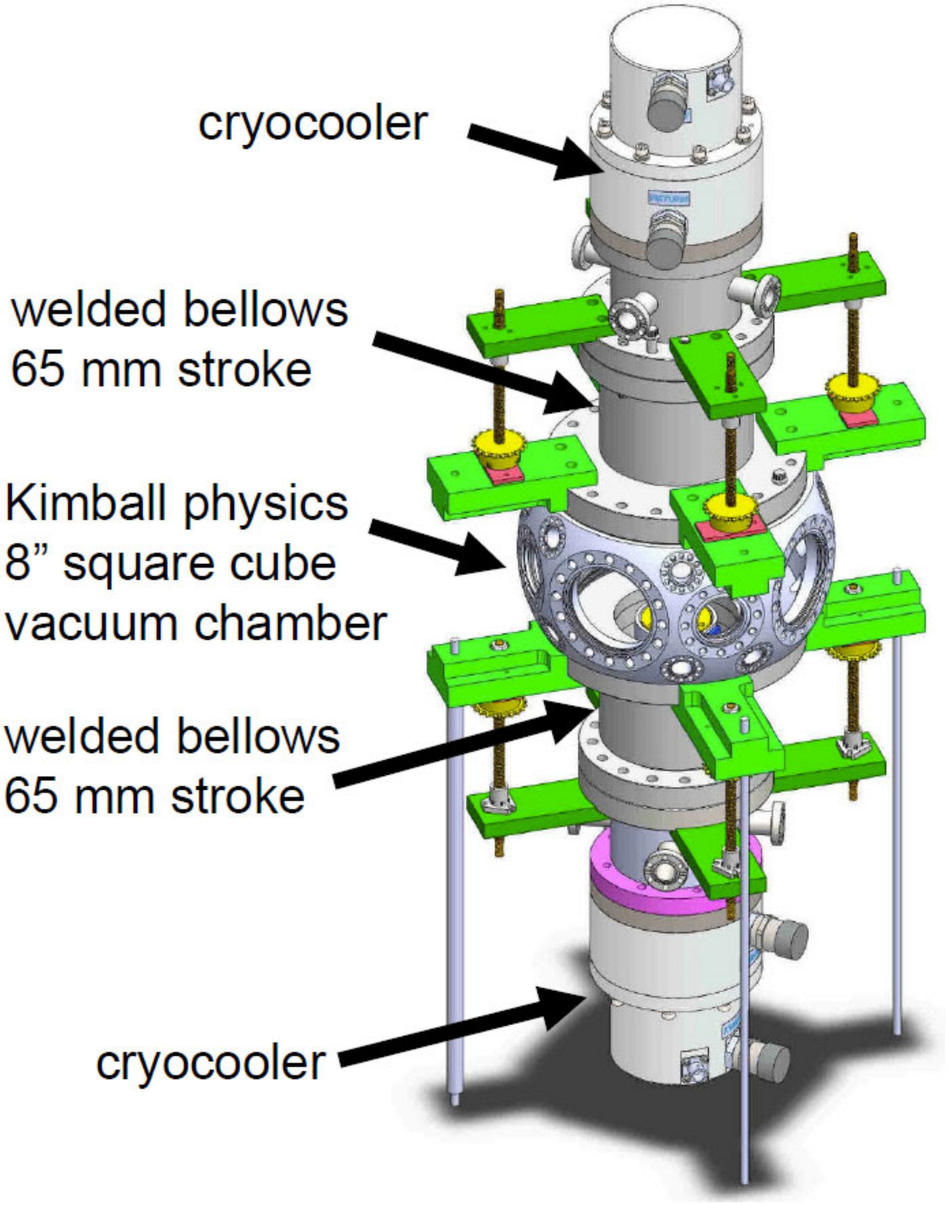

Figure 8: Solidworks drawing showing cryocoolers and welded bellows.

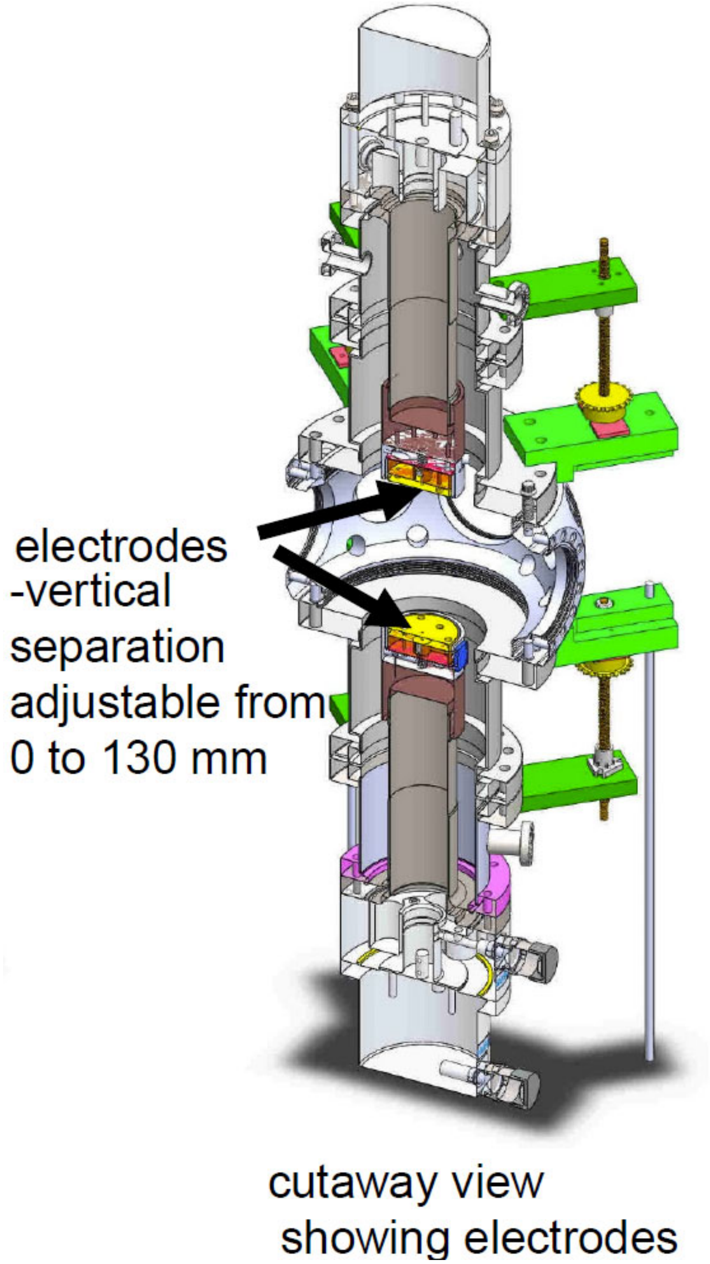

Figure 9: Cutaway view showing electrodes mounted on cryocooler cold heads.

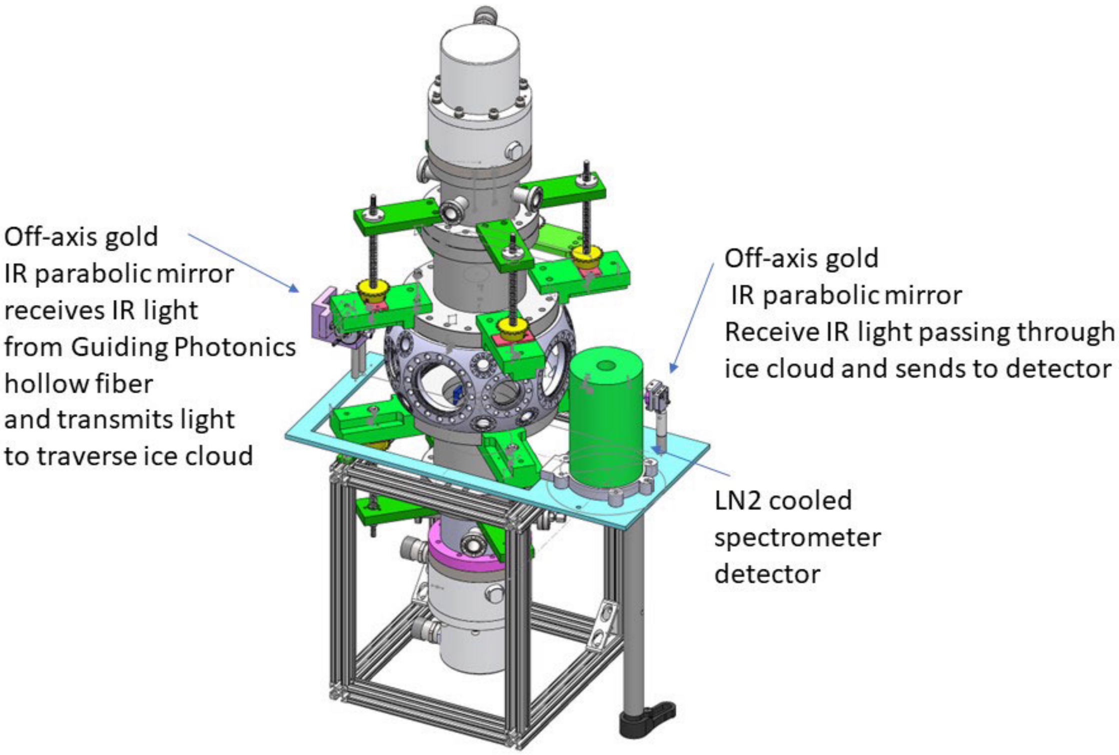

Figure 10: FTIR optics. Infrared beam from Nicolet iS50 spectrometer enters Guiding Photonics hollow fiber (spectrometer and fiber not shown). Light from fiber reflects from off-axis mirror that collimates light to form beam that passes through ice cloud in vacuum chamber. Exiting light reflects from off-axis parabolic mirror right that focuses beam into cooled detector connected electrically to spectrometer.

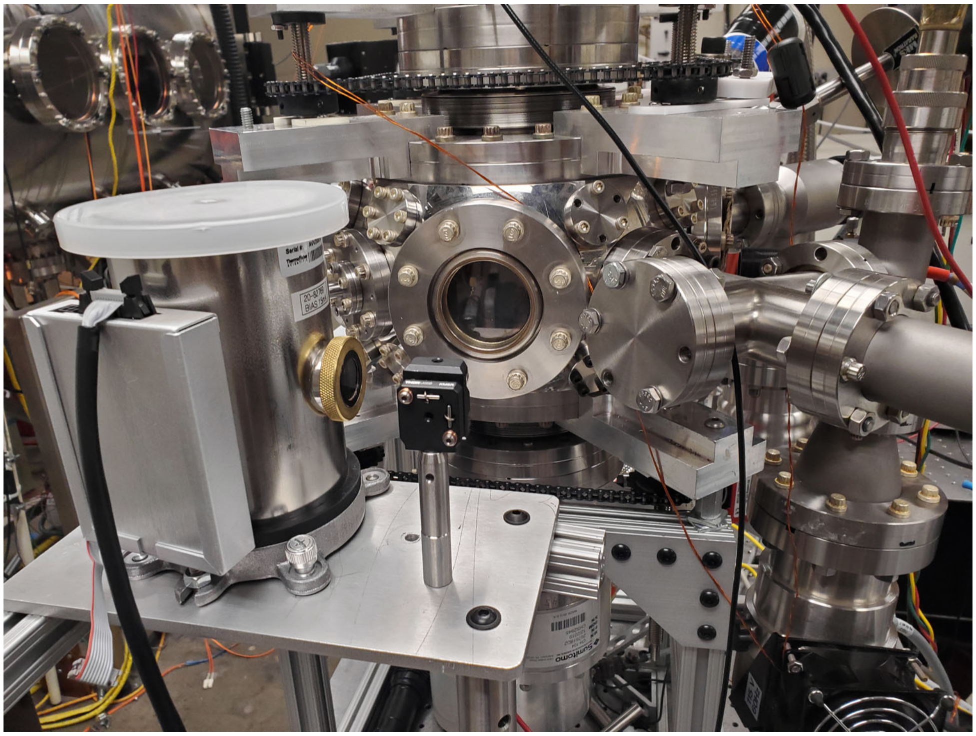

Figure 11: Liquid nitrogen cooled detector for FTIR spectrometer with mount for off-axis parabolic mirror.