A Cryosystem for Optical Evaluation of the Normal Metal Hot-elctron Microbolometer

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Abstract

We are presenting our recent results in development of a direct detector of submillimeter waves (bolometer) based on a microscopic power sensor coupled to an integrated antenna. An electrical *NEP* of 5×10^{-18} W/Hz$^{1/2}$ at 0.1 K has been demonstrated in a dc measurement. A detailed description of design of a cryogenic system for optical evaluation of this detector is presented.

Introduction

In this report we present our recent results in development of an antenna-coupled direct detector of submillimeter wave radiation – the normal metal hot electron bolometer (NHEB). Broadband submillimeter direct detectors (bolometers) are desired in certain fields of radio astronomy where large bandwidth and high sensitivity requirements are more important than a very sharp spectral resolution. An example of such a field is the study of the relict cosmic microwave background (CMB) radiation. Currently there are several projects where new kinds of structures are proposed as alternative to the present blackbody bolometers with thermistors [1-3]. Increase of the power resolution is one objective in the new development, since the new space-borne telescope projects are going to make available cold low-noise reflectors and thus create room for detectors with better sensitivity level than today's $NEP \approx 10^{-17}$ W/Hz$^{1/2}$. The other objective is to decrease the reaction time by at least one order of magnitude from the present level around 10^{-2} s. The third objective is to develop a detector technology that will make possible to build large (over 100 pixels) imaging camera arrays of detectors, preferably on a single substrate.

Electrical NEP measurements

The normal metal hot-electron bolometer has been proposed by M. Nahum *et al* in [4] and [5]. It is a microscopic power sensor containing a resistive absorber where a high-frequency current induced in a planar integrated antenna is converted to heat, which is then detected as change in the electron gas temperature. The operating principle is shortly explained in the Fig. 1.

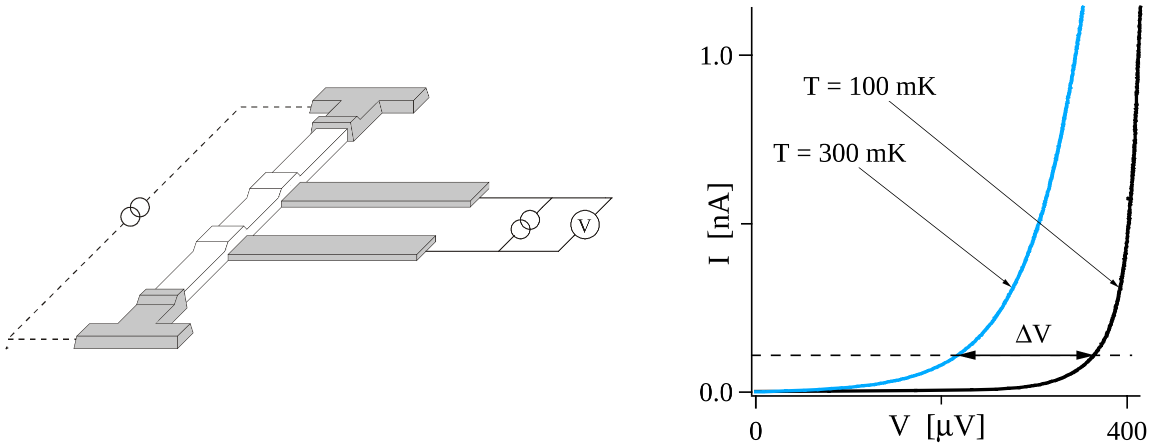

Fig. 1 Left panel – schematic diagram of the power sensor. The structure is fabricated by e-beam lithography and shadow metal evaporation from different angles. The white strip is made of normal metal (copper) and has dimensions 5×0.25×0.07 μm^3. It connects the two superconducting antenna terminals (on the ends) and serves as a resistive load for the antenna. The current induced in the antenna heats electron gas in the strip and these electrons arrive to a thermal equilibrium at a temperature higher than the lattice temperature. This is possible because the electron-phonon thermal exchange is a slower process at the operating temperatures (below 0.5 K). A thermometer consisting of two Normal metal-Insulator-Superconductor (NIS) tunnel junctions (at the middle of the strip) then reads out the electron temperature. The superconducting electrodes are made of aluminum and the tunnel barrier in the junctions is formed by the aluminum oxide.

Right panel – principle of operation of the NIS thermometer. The two junctions in series are biased with a constant current. Voltage over the junctions is then almost linearly dependent on the electron temperature in the normal electrode.

More detailed description of the sensor and its fabrication technology can be found in earlier works [6][3]. We have been working on practical development of this detector since 1997 and reported on our research progress at the previous STT symposiums. Previously our work was mostly focused on improvement of the power sensor parameters, since the ultra sensitive power sensor is the active part of the detector. We measured the so-called electrical power responsivity by heating the sensor with a small dc current. The experiments were conducted in a dilution refrigerator designed for low-frequency measurements at 0.02..2 K. The most difficult problem that we had faced was that the sensor got saturated at operating temperatures (i.e. below 0.3 K) even without any intentional heating. We explained this effect by interference from the noise induced in the wiring of our measured system. Different ways of avoiding this interference have been attempted [3] and recently we have found that the most reliable method was to install resistors of at least 10 kΩ cooled to 1.2 K in every measurement lead close to the sample under test. Some of the resistors were chosen to be 10 MΩ and installed in pairs, so that they provided the two symmetric low-noise current sources for the sensor circuit.

With this improved setup we have managed to measure the electrical noise-equivalent power $NEP = 5\times10^{-18}$ W/Hz$^{1/2}$ with sample cooled to 0.1 K and $NEP = 3\times10^{-16}$ W/Hz$^{1/2}$ with sample at 0.3 K. This corresponds to electrical power responsivities of 4×10^{9} V/W and 1×10^{8} V/W, respectively. The output noise in this experiment was dominated by the room-temperature amplifier noise and was in total 22 nV/Hz$^{1/2}$ for f_{meas} = 20 Hz (slightly decreasing with increase in frequency). The results of the experiment are shown in the Fig. 2.

Our results, as well as previously reported electrical NEP measurements [5], confirm that from the sensitivity point of view the NHEB can be very attractive as a “new generation” bolometer. The measured dependence of the electron temperature in the absorber on the applied heating power (Fig. 3) is very close to the theoretically expected $P = \Sigma\Omega\,(T^{5}-T_{o}^{5})$ (where P is the applied heating power, T is the electron temperature measured by the tunnel junction thermometer, T_{o} is the substrate temperature, Ω is volume of the absorber film and Σ is a material parameter of the absorber). This theoretical expression is based on the assumption that the electron-phonon inelastic interaction time depends on T as $\tau \propto T^{-3}$, and that would correspond to the reaction time of the bolometer close to 10^{-6} s at 0.3 K.

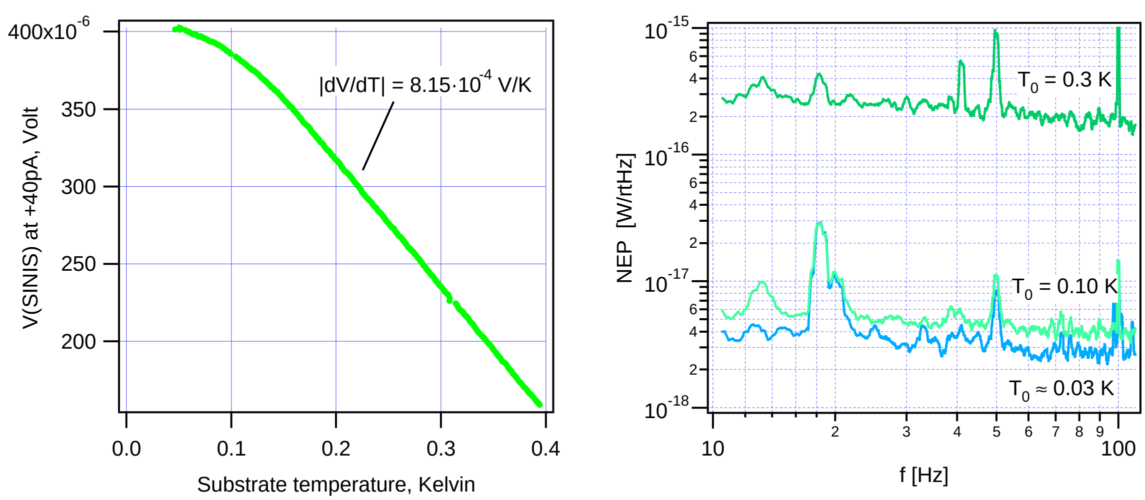

Fig. 2 Experimental results: left panel – calibration curve for the NIS junction thermometer, no heating is applied to the sensor; right panel – electrical Noise Equivalent Power of the sensor measured at three different substrate temperatures.

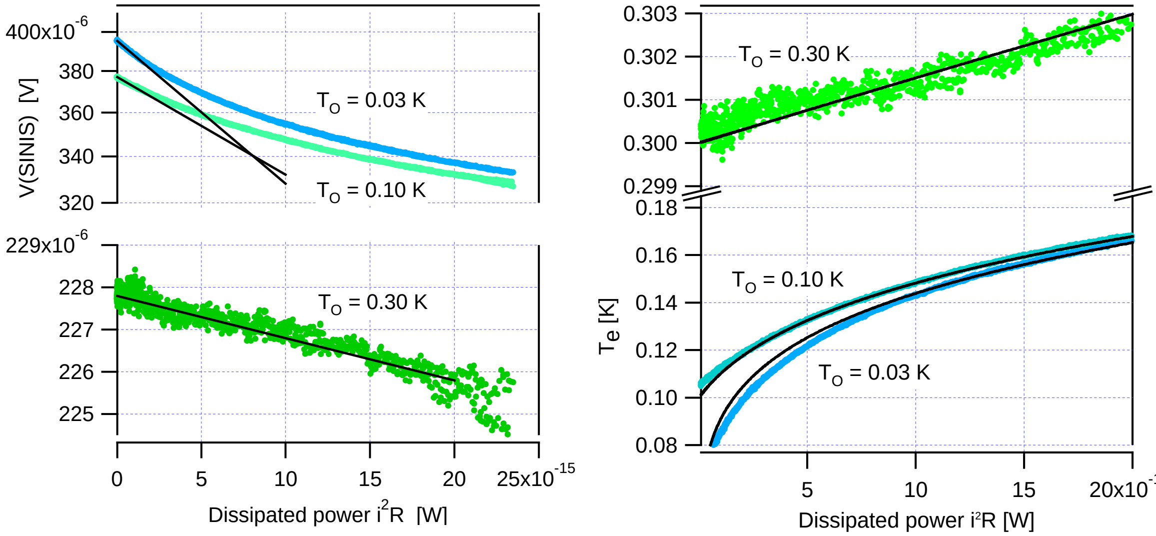

Fig. 3 Experimental results: left panel – electrical responsivity of the power sensor (voltage at the output of the thermometer vs. heating applied to the absorber) for three substrate temperatures T_o; black lines show the small-signal responsivity.

Right panel – electron temperature in the absorber computed from the output voltage using the thermometer calibration curve (see fig. 2); black curves are the fits obtained with the expression $P = \Sigma\Omega\ (T^5\text{-}T_o^5)$ and a single fitting parameter $\Sigma = 2.5\times10^{-9}$ W μm^{-3} K^{-5} for all three curves.

Design of a mm-wave cryosetup

At this stage we are considering an experiment where not only the electrical parameters of the power sensor, but also the optical responsivity of the bolometer as whole could be measured. This requires a measurement setup that would have an optical input with controlled throughput, and at the same time would allow cooling the detector to at least 0.3 K. In the literature one can find successful examples of the similar systems built for testing of heterodyne mixers; however almost none of them involve cooling to below 4.2 K. Some more traditional low-temperature bolometer cryostats have cooling even down to 0.1 K, but their optical setups are adapted for blackbody bolometers and based usually on the Winston concentrator coupling. In the cryogenic system that we are building at the moment we are trying to combine solutions from the both types of detector cryostats and to suit the special experimental requirements for an antenna-coupled bolometer.

Cornerstones of the design

Since we see the CMB studies as a possible potential application for the detector, we have decided to choose for our setup a frequency band corresponding to 3..5 K blackbody emission (180..300 GHz). The heavy radiation load at higher frequencies that could both overload the sensor and overheat the substrate will be cut off by a metal-mesh low-pass filter with sharp edge at 450 GHz [7]. Further, a neutral density (ND) filter can be used to attenuate the incoming radiation at all frequencies. To provide a certain frequency resolution and to avoid overriding dynamic range of the bolometer we would like to limit the fractional bandwidth of the detector to about 20%. This band is going to be defined mostly by the frequency response of the double-slot antenna that we are going to use.

The double-slot antenna is attractive for three reasons:

1. It provides a natural band-pass filter.
2. It has a fairly narrow radiation pattern (compared to *e.g.* the log-periodic antenna), which is important since we need to control the whole throughput of the antenna.
3. It can be matched to a low-resistive load (below 50 Ω). This allows to make the absorber strip in the sensor short, which means a smaller film volume and hence a higher responsivity.

Both the sensor structure and the antenna are fabricated on a flat silicon substrate. To provide a proper coupling to the antenna through the backside of the substrate the substrate will be glued on a hyperhemispherical silicon lens [8]. The hemisphere diameter is 13.7 mm and it is extended with a silicon slab so that the antenna is placed 2.20 mm behind the center of the sphere. The combined lens antenna should then have 30 dB-beamwidth of about 34º (10 dB-beamwidth of 16º). The pattern can be approximated by a gaussian beam diverging from the antenna. This gives a fairly narrow beam, but we preferred to convert it to a converging beam by means of a 50 mm TPX dielectric lens (Fig. 4). This allowed us to choose the optical window and the infrared filters of a small diameter (1 inch), which should help to decrease the overall radiation load on the cryosystem.

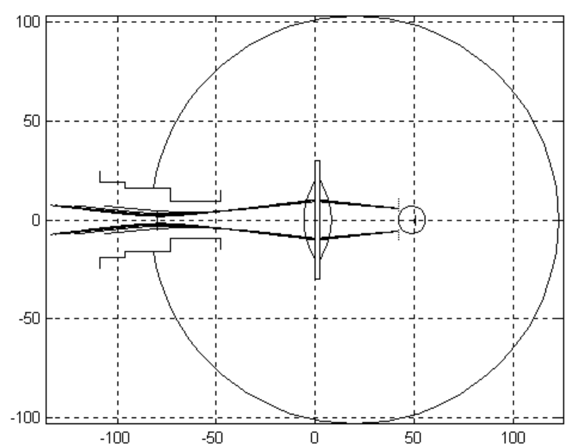

Fig. 4

Ray traces in the proposed optical arrangement (at the –8.7dB relative power level) for frequencies from 180 GHz to 420 GHz. The components on the drawing are the filter unit aperture, the dielectric lens and the hyperhemispherical lens (shown by a small circle). The traces are calculated in the assumption of the gaussian beam shape.

For cooling of the detector we have chosen a closed-cycle ^{3}He-cryocooler that can reach temperatures down to 0.27 K. This unit is manufactured by CEA/DSM/DRFMC/Service des Basse Températures, Grenoble, France. It does not require any external pumps and could be conveniently mounted in a pit in the cold plate of an 8-inch ^{4}He-dewar from Infrared Laboratories (Fig. 5). This is a robust and inexpensive solution compared to an adiabatic demagnetization refrigerator or a dilution refrigerator for cooling to 0.1 K or below. Another consideration was that due to the high total radiation load in the experiment the sensor would have *T* [electron gas] > 0.3 K anyway, that is even if the substrate temperature would be below 0.1 K.

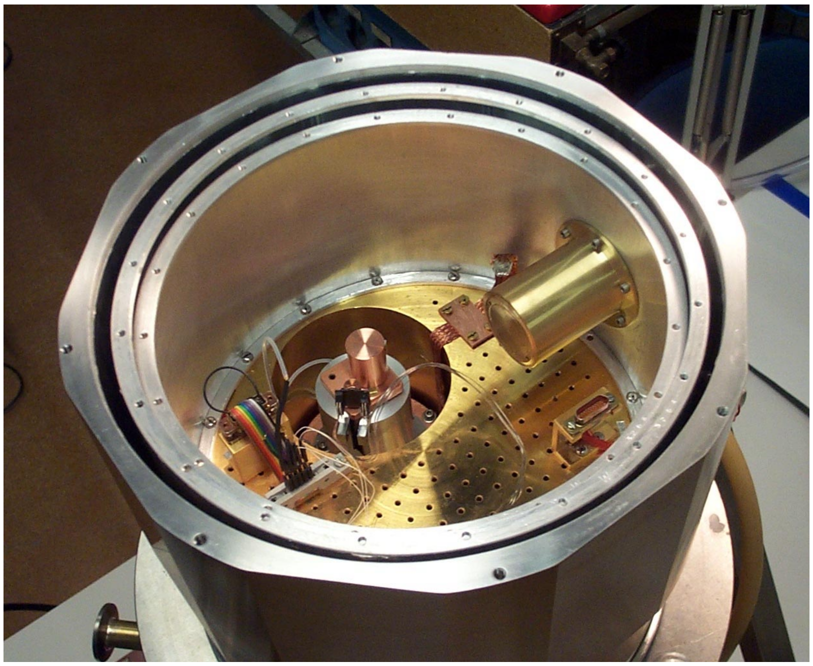

Fig. 5 The current phase in installation of the new system. One can see the ^{3}He-cryocooler mounted in a pit in the 2 K-cold plate of an 8-inch HDL dewar from Infrared Labs and a long baffle (here blanked), which will accommodate the stimulator and the filter unit. This longer baffle is exchangeable with a shorter one for the filter unit only.

As for a source of incident radiation we have considered two possibilities. One option is to observe an external blackbody source with a known spectral intensity distribution through an optical window in the dewar. To avoid drifts in the measurements one can modulate the radiation by mechanical chopping between a 295 K source and a 77 K source. A different option is to place a blackbody source inside the dewar. There are certain advantages with the latter solution: peak of the frequency spectrum can be placed at the center frequency of the bolometer band by heating the blackbody to a proper temperature (around 5 K for 300 GHz); low intensity of the source makes possible measurements without an ND filter, which otherwise introduces additional uncertainty in the spectral distribution (because of internal interference fringes); also modulation of the source (possibly up to 100 Hz) can be done simply by modulating the heating current. We are going to employ a commercially available thermal source – “stimulator” – from Haller-Beeman Associates, Inc. It will be placed in the focus of a Winston horn, thus spreading the emitted radiation to a uniformly illuminated spot about 10 mm in diameter (the larger aperture of the horn).

By arranging a detector mount and the dielectric lens on a compact optical bench inside the dewar it is going to be possible to use the same alignment both for measurements employing the optical window and for the measurements employing the stimulator. In the second case the stimulator is mounted just behind the optical window inside the dewar, a filter set is moved in front of it, and the optical bench with the rest of the setup is shifted back to keep the distance from the antenna to the filter's surface the same (Fig. 6).

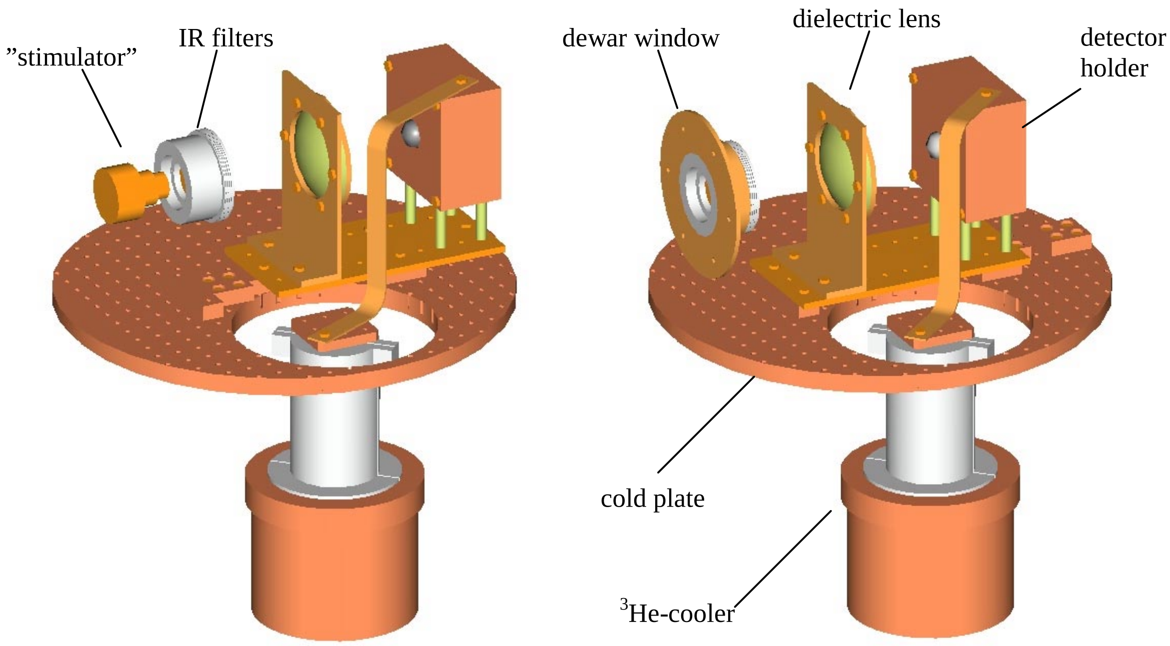

Fig. 6 Computer-generated images of the components inside the ^{4}He dewar. Left side – option for measurements with an internal stimulator; right side – option for measurements with irradiation through the dewar window. The two configurations can be exchanged by simple re-mounting of the filter unit and shifting the smaller optical bench along the optical axis.

Formulation of the experiment

From the developer's point of view it is interesting to verify the correctness of the theoretical estimations of the bolometer performance, which are based on what is known about the power sensor's performance. However, we need to consider at least the combination of the power sensor and an antenna as a minimal receiving unit. Since we are planning that our detector is going to be used for a different branch of research we need to specify the bolometer sensitivity independent of an actual observation system. But at the same time it is less straightforward to measure intensity and spectrum of the radiation at the input of the antenna in contrast to measuring it at the input of a cryosystem as whole. One can formulate this problem in terms of the following algebraic expression:

$$P(f) = C(f) \cdot T_2(f) \cdot T_1(f) \cdot F_2(f) \cdot F_1(f) \cdot K(f)\,.$$

Here f is frequency of the radiation, P is the power spectral density incoming the power sensor, K is the power spectral density of radiation from a source, and the rest of the functions describe the transmitting properties of intermediate components in the radiation coupling system:

F_1 is transmission function of the low-pass filter,

F_2 is transmission function of the neutral density filter,

T_1 is transmission function of the dielectric lens,

T_2 is transmission function of the hyperhemispherical antenna lens, and

C is the coupling coefficient for the planar integrated antenna.

The first of our goals in this formulation is to determine the function P as accurate as possible, because then we can calculate the electrical responsivity of the sensor

$$S_e(f) = \left(dV/dP\right)_f$$

(where V is voltage at the output of the sensor) for heating by a high-frequency excitation and compare it to the theoretical predictions and to the results obtained with a dc heating.

The second goal is to specify the optical responsivity of the detector with a silicon lens antenna, which is

$$S_o(f) = \frac{dV}{d\left(P(f)/C(f)/T_2(f)\right)} = \frac{dV}{d\left(K(f) \cdot F_1(f) \cdot F_2(f) \cdot T_1(f)\right)}\,.$$

The $K(f)$ can be computed from the Planck's expression for blackbody radiation. $F_1(f)$ is generally specified by the manufacturer, however some uncertainty can be due to that the filter's performance can be different for rays incident under a finite angle to its surface. $F_2(f)$ is specified as a constant, but as already mentioned interference due to reflections between the two surfaces of the ND filter substrate can lead to a ripple in the transmission curve. $T_1(f)$ and $T_2(f)$ can be computed to a good approximation knowing the properties of the materials (TPX and silicon).

In the initial experiment we plan to compute all these function and substitute them into the formulae in order to evaluate the data. Later on we intend to characterize the components individually by substituting some of them. For example, ND filter can be avoided if we use the internal stimulator as a source; by substituting our test bolometer with a bismuth bolometer with known responsivity we can get information about the $P(f)$, etc. Also using a Fourier Transfer Spectrometer as a narrow-band radiation source is an option for a more accurate calibration of the system.

Conclusions

We have further improved the electrical NEP performance of the normal metal hot-electron bolometer by introducing cold resistors in the sample wiring in our measurement system. *NEP* = 5×10^{-18} W/Hz$^{1/2}$ at 0.1 K has been achieved. Now we are working on an experiment where we could measure the optical responsivity of the detector in the 1 mm wavelength range. A new cryogenic setup for this purpose has been designed. The cooling facilities of this setup have already been put in operation and the quasioptical components are in the process of installation.

Acknowledgements

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