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On-orbit performance of the RHESSI cryocooler

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Abstract

The Ramaty High Energy Solar Spectroscopic Imager (RHESSI) spacecraft was launched on February 5, 2002. With more than a year of operation on-orbit, its Sunpower M77 cryocooler continues to maintain the array of nine germanium detectors below 80 K. Trends have begun to emerge in cryocooler power and vibration, suggesting that the cooler's operating point is slowly changing. Possible causes are identified and discussed.

Keywords: Cryocooler; Stirling; Space cryogenics

1. Introduction

The Ramaty High Energy Solar Spectroscopic Imager (RHESSI) spacecraft (Fig. 1) uses a spectrometer mounted behind a nine-element rotating-grid telescope to image details on the disk of the sun and perform high-resolution spectrometry of solar flares, coronal mass ejections, and other energetic solar processes. The spacecraft and instrument were designed for a minimum two-year lifetime, and have recently been approved for at least a third year of operation. Launched in February 2002 after a number of delays, RHESSI has observed hundreds of flare events occurring near and slightly after the peak of the eleven-year solar cycle, including the first detailed observations of γ-ray flares [1,2].

The RHESSI spectrometer uses nine high-purity germanium detectors, mounted in a vacuum shell on an aluminum coldplate. The coldplate is cooled by a Sunpower M77B Stirling cycle cryocooler [3] (Fig. 2). While the detectors themselves have no measurable dissipation, each detector requires two FET amplifiers operating at around 150 K, each dissipating approximately 30 mW. The coldplate is connected by a thermal link to the end of the cryocooler coldfinger, while the FET's and a thermal shield are strapped to the midpoint on the coldfinger, approximating the function of a two-stage cryocooler.

1.1. Early power trend

The cryocooler was first powered on approximately 6 h after launch. The cooldown on-orbit slightly lagged the last cooldown in the lab, reaching 75 K in 7 days [4]. Initial operating parameters matched lab conditions very well.

It was 6 months after launch that the instrument team noticed an apparent trend in the cryocooler power, increasing at a rate of 13–15 mW each day (Fig. 3). The cooler is driven with a constant drive voltage, so the power trend was unexpected and unexplained. As this trend has continued and perhaps accelerated, we have examined possible explanations for this trend, and attempted to provide a prognosis for continued operation of the cooler.

2. Performance investigation

The RHESSI cryocooler had seen approximately 11,000 h of operation by the time it was launched, and has accumulated an additional 14,000 h on orbit. When the power trend became noticeable, the health of the cooler became a concern for the project. Though the RHESSI cryocooler remains the most likely cause of the symptoms that are described here, there has been a

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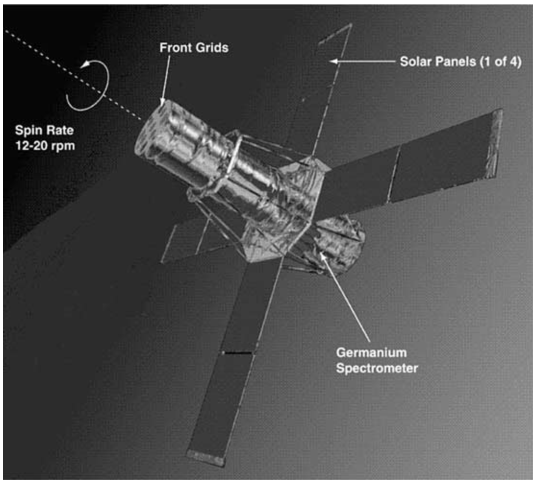

Fig. 1. The RHESSI spacecraft.

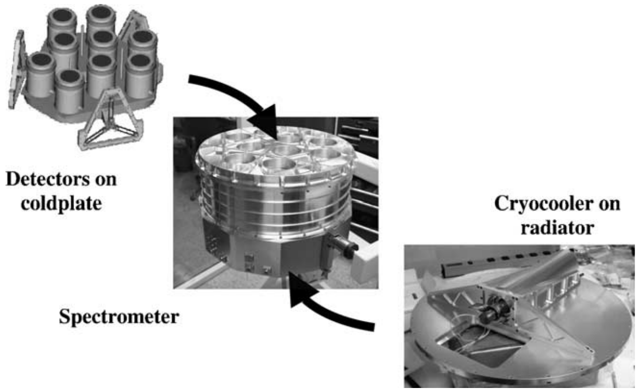

Fig. 2. The spectrometer contains nine detectors and the cryocooler. The cryocooler mounting plate also serves as its radiator, and as the bottom vacuum plate for the spectrometer.

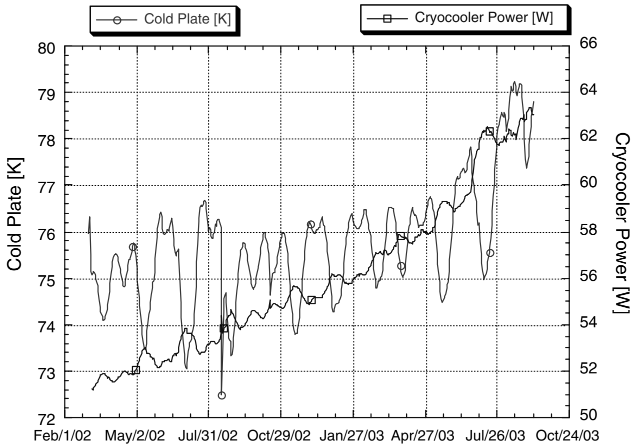

Fig. 3. Cryocooler cold plate temperature and power trend.

great deal of effort to identify all reasonable alternatives, and systematically examine them all.

2.1. Cryocooler power

This examination must begin with an understanding of how the RHESSI cryocooler is driven and monitored. Like all Sunpower coolers, the M77B contains a moving-magnet motor which is driven by a 58.5 Hz AC waveform. This waveform can be almost anything from a pure sine wave to an unfiltered square wave. For the RHESSI mission, a Cryo Power Converter (CPC) electronics box takes power from the 28 V spacecraft bus and a digital sine wave function from the Instrument Data Processing Unit (IDPU) to drive the output of a pulse-width modulated power amplifier for the cryocooler. In order to attenuate the vibration of the cooler, a second motor was added to the M77 by Sunpower to drive a counterbalance mass, mounted inside the cryocooler pressure case. The CPC contains a small linear amplifier, driven by a second sine function from the IDPU, to drive the counterbalance mechanism. The current into the CPC is measured by a current shunt. The power into the cryocooler is inferred by subtracting the known resistance of the cryocooler power cable and inefficiency of the CPC. Power that is reported for the cryocooler includes the power for the balancer.

The cryocooler is mounted on a plate that does double duty as the base plate of the RHESSI spectrometer and as the cryocooler radiator. The temperature of the radiator can be modulated by a 30 W stay-alive heater, driven on a duty cycle controlled by the IDPU.

Power into the cryocooler is affected periodically by perturbations of the spacecraft bus voltage and the spectrometer radiator temperature. After the first 6 months of operation, it was clear that in addition to these shorter-term variations, a background trend was emerging in the cryocooler power, increasing on average 13–15 mW per day. This was not initially accompanied by an increase in either the cold end or warm end temperatures on the cryocooler (Fig. 4). It was, however, accompanied by an increase in the vibration of the

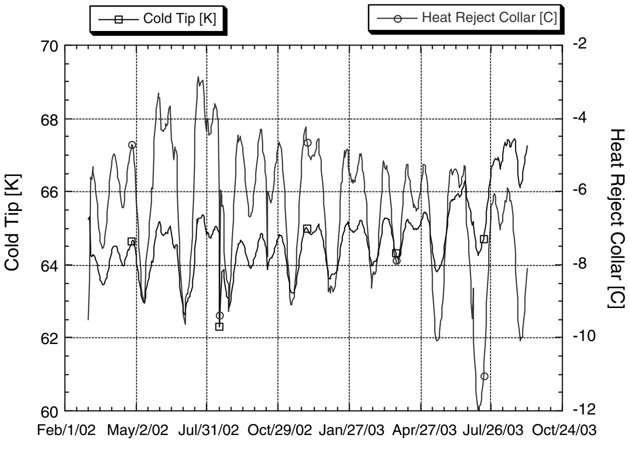

Fig. 4. Cryocooler cold end and warm end temperatures.

spectrometer. The trend in cryocooler power has continued over the duration of the mission, increasing in rate at the beginning of 2003, but remaining consistent since then.

2.2. Cryocooler vibration

The germanium detectors used on RHESSI are typically quite sensitive to microphonic noise pickup, so an accelerometer was designed into one of the small electronics boxes mounted on the spectrometer shell. The rms value of the accelerometer signal is used by spacecraft controllers to adjust the phase and amplitude of the counterbalance waveform. The RHESSI detectors turned out to be rather insensitive to microphonics, so the counterbalance waveform is only adjusted once every few months.

The first adjustment, at the end of cooldown, was able to reduce spectrometer vibration to 10 mg rms (Fig. 5). The next adjustment, nine months later, was only able to reduce it from 16 mg down to 13 mg. The most recent adjustment, on June 25, 2003, for the first time coincided with a jump in the cryocooler power, of about 1 W magnitude, and gave a temporary appearance that the cryocooler power trend was rapidly accelerating. This may be an indication that the operating mode of the balancer has changed in some way, but does not necessarily mean that the balancer is deteriorating.

A linear-drive cryocooler like the M77 typically has very periodic vibration, so changes in the rms vibration amplitude implies either a non-periodic (noisy) nature, or vibration at upper harmonics of the drive frequency that are not compensated by the balancer.

Noise at the drive frequency of the cooler can be caused by flow instabilities in the working fluid, friction between moving parts, or noise in the electronics. Flow instabilities should only change as the flow passages change, associated with wear or contamination in the machine. Friction in any mode of cryocooler operation would also be accompanied by wear and contamination. Both of these possibilities would imply premature degradation of the cryocooler. Noise in the electronics, either the cooler drive or accelerometer signal conditioning, has not been eliminated, but seems less likely under the circumstances than a mechanical explanation.

2.3. Cooler efficiency

The amount of thermodynamic work done by the cryocooler is determined by the temperature ratio across the cooler, and the amount of refrigeration being supplied:

$$W = (T_{\mathrm{H}} - T_{\mathrm{L}})/T_{\mathrm{L}} * W_{\mathrm{refrigeration}} \tag{1}$$

An efficiency parameter for the cooler can then be defined as the ratio of thermodynamic work to electrical input power:

$$\eta = P/W \tag{2}$$

The heat reject temperature and the cold tip temperature of the cooler are both measured directly, and the electrical power, as described above, is inferred. The power of refrigeration is not measured in any direct sense at either the cold tip or the mid stage, but the temperature difference between the cold tip and the spectrometer coldplate may be useful in inferring any trend in the cryocooler load. This temperature difference has in fact increased slightly over the duration of the mission, raising the possibility that the heat load on the cooler is increasing (Fig. 6). One of the elements in the thermal path between these two points is a sapphire bar, which has a maximum conductivity around 40 K. When the net temperature dependent conductance of this path is taken into account, the calculated heat load is constant within 3%. If we assume that the load on the coldfinger mid-stage is also constant, we can calculate our efficiency parameter based on a nominal, fixed refrigeration load (Fig. 7). This parameter has dropped

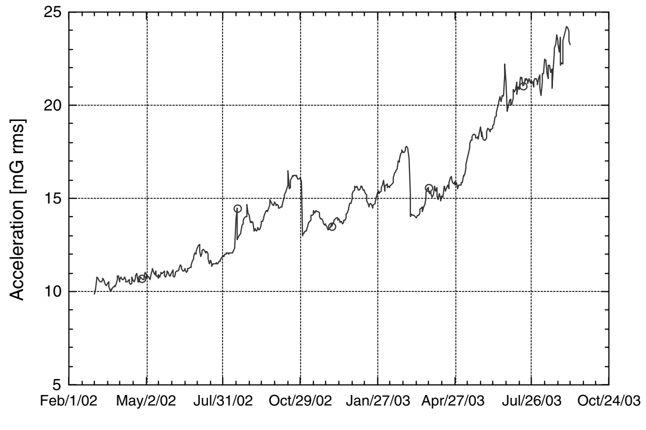

Fig. 5. Daily average of spectrometer vibration.

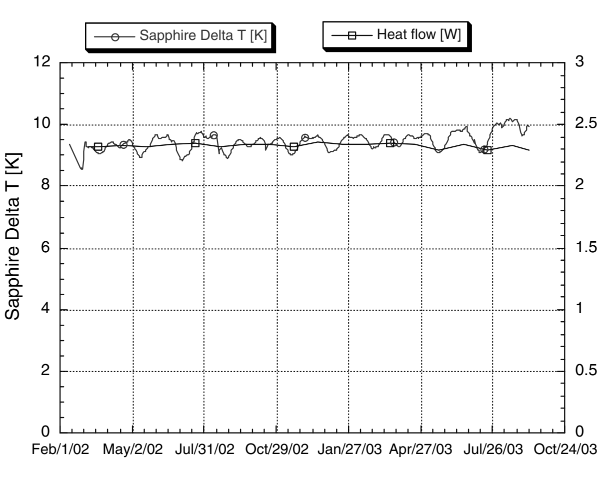

Fig. 6. Sapphire temperature difference.

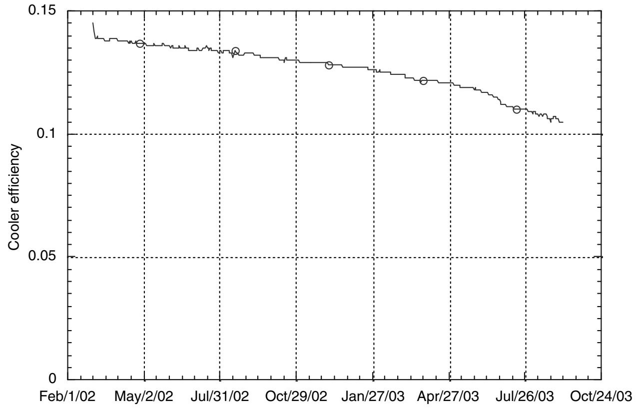

Fig. 7. Crycooler efficiency.

by about 20% since the start of the mission, which again is consistent with degradation of the cooler.

2.4. Dissipation in the CPC

As discussed above, the power into the cryocooler is only measured indirectly. The extra power has been assumed to be dissipated in the cryocooler, but might also be attributed to added dissipation in the balancer or the CPC. The excess power at this point in the mission, about 10 W, is comparable in magnitude to the nominal dissipation in the CPC, and in fact the CPC temperature has risen at about the same rate as the cryocooler power (Fig. 8). The magnitude of the rise, however, is consistent with the nominal efficiency of the CPC, until the balancer adjustment on June 25, 2003. At this point the CPC temperature jumps disproportionately to the increase in power. This again suggests some change in the mode of operation of the balancer at that time.

Power dissipation in the cryocooler/counterbalance assembly may be inferred from its temperature, which is best represented by the sensor on the cryocooler's heat reject collar. This temperature shows variations on hourly and monthly time scales, but has remained within constant bounds until May 2003 (Fig. 4). This is partly due to the cooler's stay-alive heater, which has been used by spacecraft controllers on a weekly basis to provide coarse regulation of the spectrometer radiator. When the cryocooler power and radiator heater are added together, the power into the radiator is seen to be almost constant (Fig. 9). Again, the cryocooler temperature data is consistent with the presence of gradual degradation in the cryocooler.

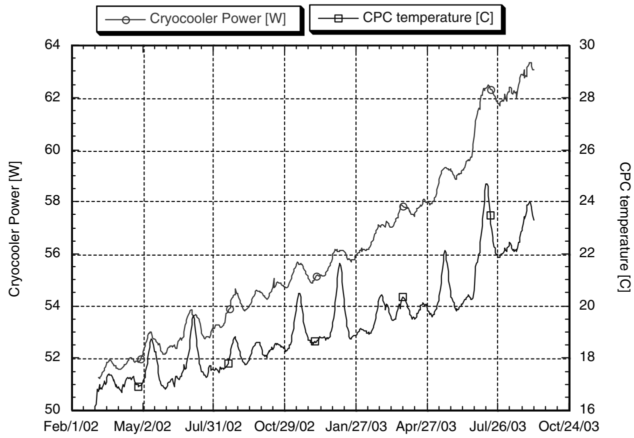

Fig. 8. Cooler power and CPC temperature.

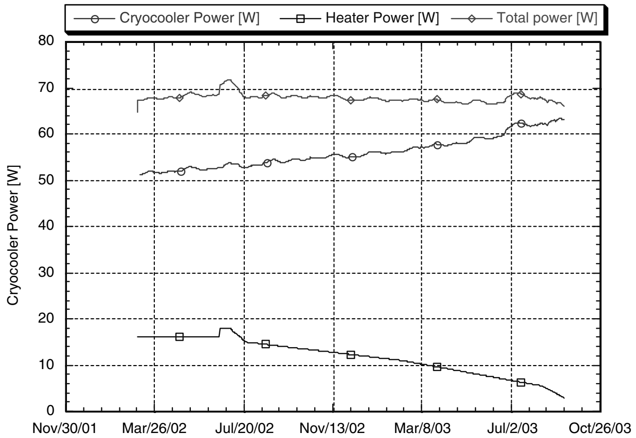

Fig. 9. Power on the spectrometer radiator. The CPC radiates its power separately.

3. Conclusions

Though the RHESSI cryocooler continues to meet its performance specification, the system shows symptoms that are consistent with gradual degradation of the cooler. These symptoms include increases in the cryocooler power and vibration, and a decrease in cryocooler efficiency. The trend does not seem to be accelerating, so the remaining life of the cryocooler may still be quite long. The cryocooler power will be increased as necessary to maintain the detectors below 85 K, and its performance will be monitored through the end of the mission.

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