The Standard New Astronomy Cryostat for SOFIA: A Design for Cryogen-Free Infrared Astronomy

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Abstract

Astronomy at infrared wavelengths requires optical instruments that operate at low temperatures, which is typically done using liquid cryogens such as nitrogen and helium. These cryogens are costly and limit the operational time of the science instrument. The Standard New Astronomy Cryostat for SOFIA (SNACS) will provide a design for a helium cryocooler-cooled cryostat that meets the stringent airworthiness requirements of the Stratospheric Observatory for Infrared Astronomy (SOFIA) and can be used by future instrument builders to reduce the cost and risk of their instrument design and development. The SNACS dewar will provide approximately 3.4 x 10^{-1} m^3 of science space on an airworthy platform for optical instruments as massive as 300kg and operating at temperatures as low as 4K using pulse tube cryocoolers. This research examines the range of optical design configurations and focal planes that can be accommodated by SNACS. 1

SOFIA: The World's Most Powerful Infrared Observatory

- Operational altitude of 12-14 Km is above 99% of atmospheric water vapor
- Wide range of wavelengths with high resolution (5μm at R=200 to 450μm at R=2000)
- Capable of accommodating a variety of optical instruments

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The First & Second Generations of SOFIA

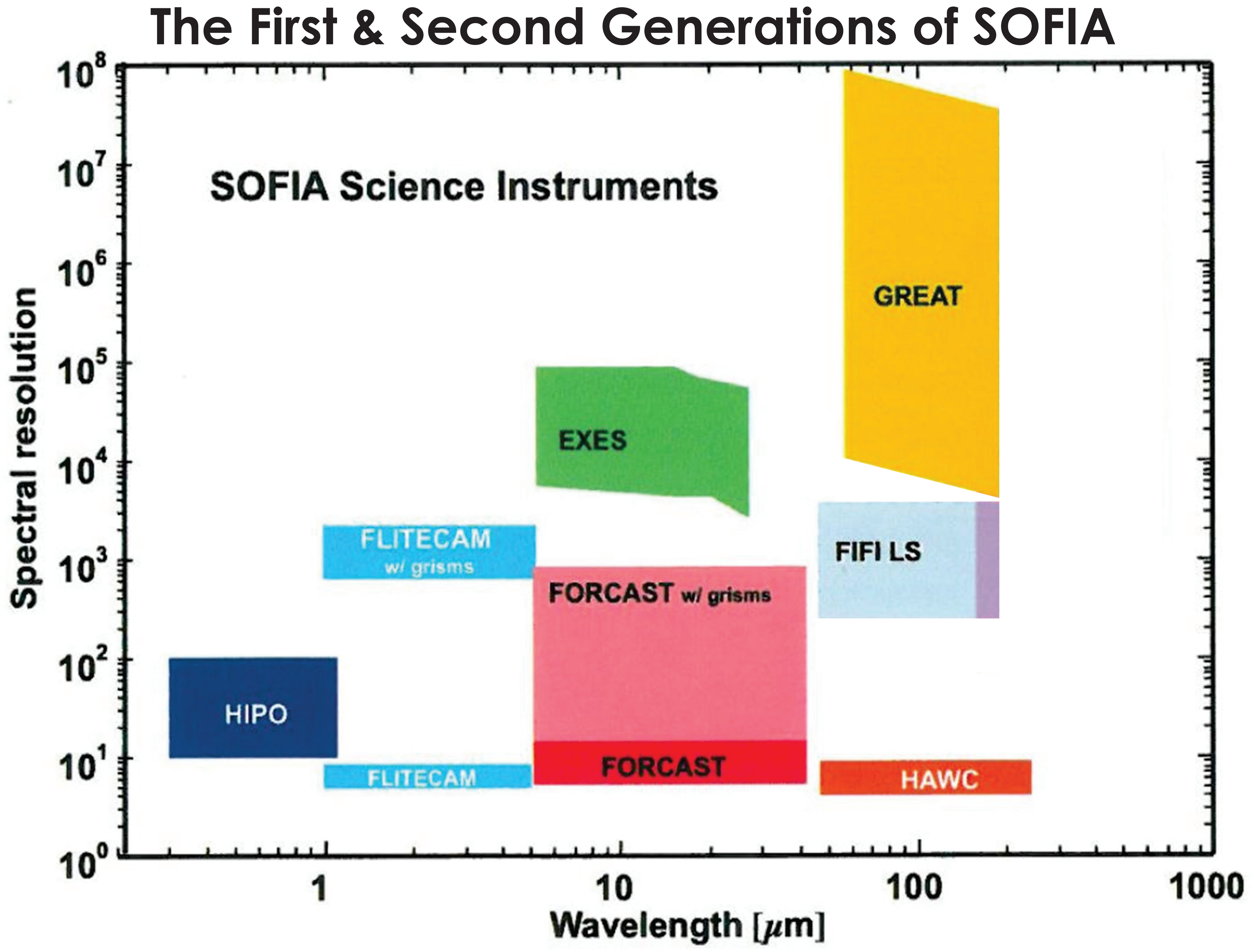

Figure 3-1 Resolving Power vs. Observable Wavelengths for Existing SOFIA Science Instruments 3

SNACS Dewar Design

X-Section Configuration 1

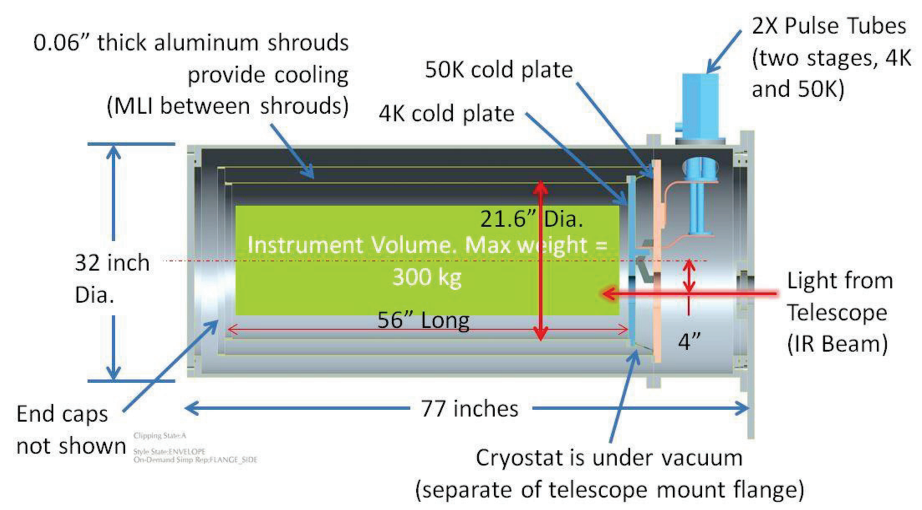

Figure 4-1 Cross-Section of Configuration 1

X-Section Configuration 2

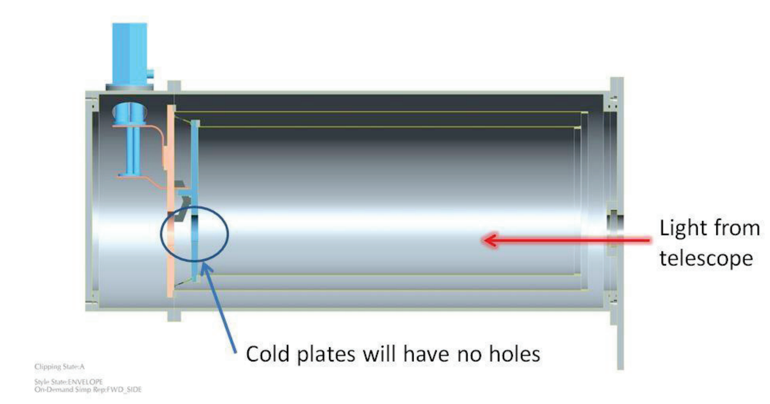

Figure 4-2 Cross-Section of Configuration 2 4

Call for New Science Instruments

To demonstrate the utility of SNACS for 3rd Generation SOFIA science instruments, we show the opto-mechanical designs of two existing SOFIA science instruments repackaged into the SNACS cold volume using Radiant Zemax® optical design software and Pro-E®. Depicted below:

- **FORCAST** - **F**aint **O**bject Infra**R**ed **CA**mera for the **S**OFIA **T**elescope
- **EXES** - **E**chelon-Cross-**E**chelle **S**pectrograph

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Preliminary Optical Packaging Results

FORCAST Optical Prescription Repackaged in SNACS Cold Volume

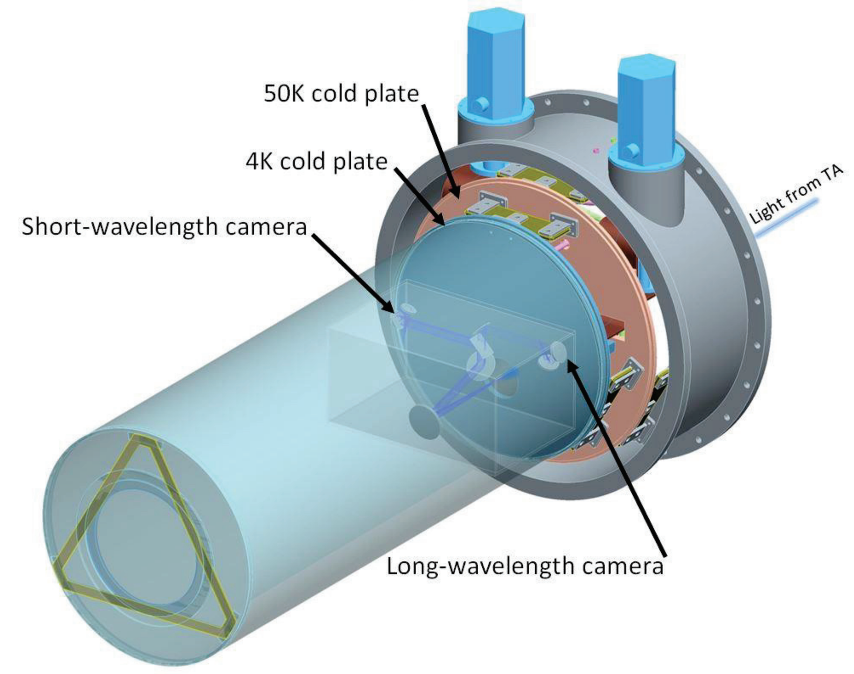

Figure 6-1 FORCAST optics are shown "prepackaged" in a design box and fit into the SNACS cold volume using Configuration 1

EXES Optical Prescription Repackaged in SNACS Cold Volume

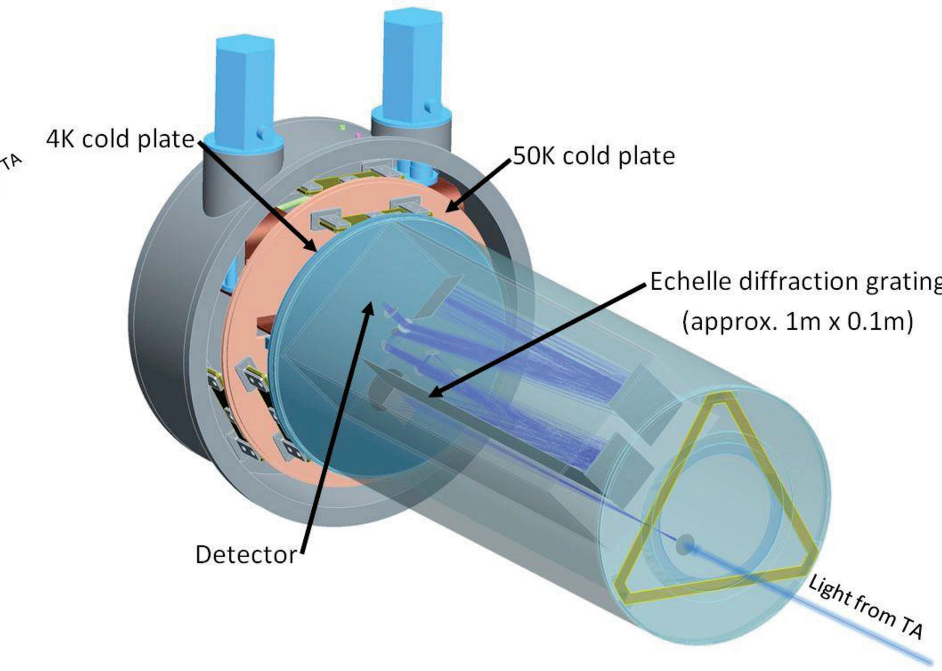

Figure 6-2 EXES optics are shown "prepackaged" in a box and then easily placed into the SNACS cold volume using Configuration 2 6

Acknowledgements

I would like to thank Ali Kashani, Jeffrey Feller, Ben Helvensteijn and Stefan Rosner for discussion on PTRs and cryocoolers; Eric Burgh, Erin Smith and the rest of the SNACS Team for their assistance and support during this research project. I would also like to thank Zaheer Ali, Russ Billings, Samantha Grimaldo-Uribe, the USRA staff & the STAR team for their guidance & advice. Special thanks to Jeffrey Van Cleve , Chris McCarthy, and Greg Stoehr for their mentorship and dedication to science education.

References

Box 3: Figure 3-1 From *The Science Vision for the Stratospheric Observatory for Infrared Astronomy © 2009*
Box 4: Figure 4-1 and 4-2 created by Earl Daley for the SNACS Preliminary Mech Concept 6/27/13
Box 6: Initial EXES design courtesy of EXES team (UC Davis); FORCAST prescription provided by L. Keller (Ithaca Univ.)
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The Stirling Cycle

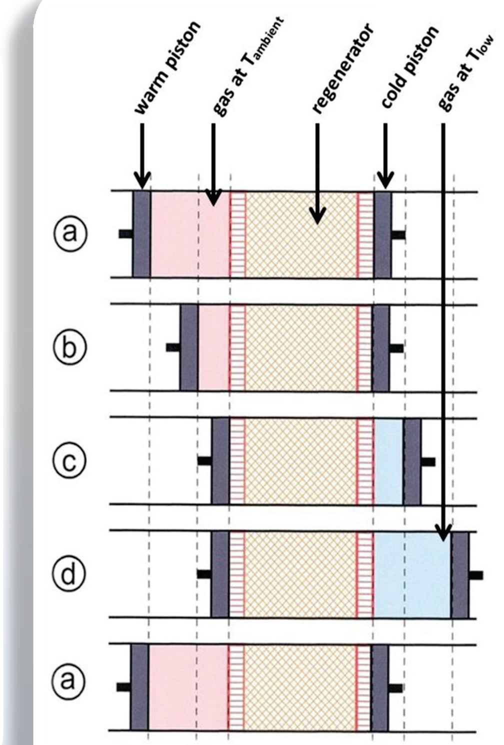

Figure 7-1 The Stirling Cycle

a → b: The warm piston moves to the right while the cold piston is fixed. The compression at the hot end is isothermal, so heat Q_a is given off to the surroundings at ambient temperature T_a.

b → c: The hot gas enters the regenerator with temperature T_a and leaves it with temperature T_L as it gives off heat to the regenerator material.

c → d: The cold piston moves to the right while the warm piston is fixed. The expansion is isothermal and heat Q_L is taken up. This is the useful cooling power.

d → a: The two pistons move to the left while the total volume remains constant. The gas enters the regenerator with low temperature T_L and leaves it with high temperature T_a so heat is taken up from the regenerator material. 7

Pulse Tube Refrigeration

Pulse tube refrigeration (PTR) is similar to the Stirling Cycle, but the cold piston is replaced by the inertia of the gas itself.

- Gas moving out of regenerator into pulse tube (PT) does work on gas at the hot end of the pulse tube which warms.
- Heat is removed at the hot end to keep it at constant temperature. The gas at the cold end of the PT does work and therefore cools.
- When the cycle reverses, the gas at the PT warm end has less energy to move heat this way. The gas at the cold end warms, but not to its starting temperature.

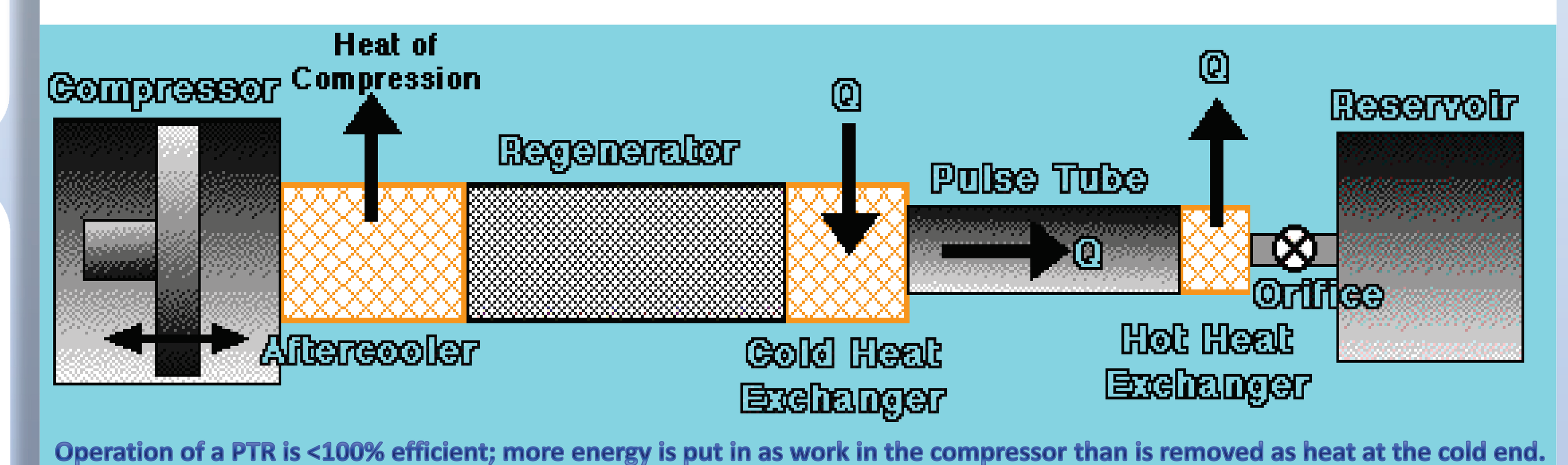

Figure 8-1 Schematic Of A High Frequency (> ~ 30 Hz) Pulse Tube Employing a Linear Compressor 8

Pulse Tube-Compressor Cryocooler System

- SNACS will employ two 2-stage He pulse tube refrigerators (pulse tube cold head & compressor)
- Each PTR is a closed volume system so the amount of gas in the pulse tube and the compressor is constant.
- A phase difference between the oscillating pressure and oscillating mass flow in the pulse tubes creates a unidirectional enthalpy flow from the regenerator toward the reservoir.
- Cold straps are employed to attach the pulse tube cold head to thermal loads at 50K and 4K

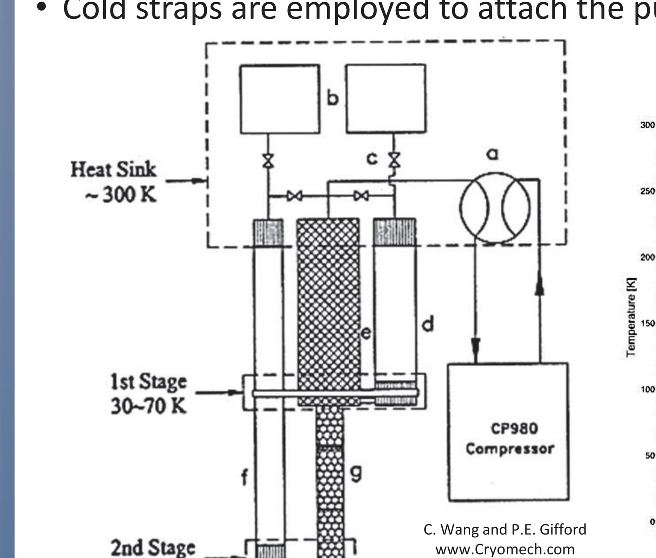

Figure 9-1 Schematic of a Cryomech 2-stage PTR: **a)** rotary valve; **b)** 1st and 2nd stage reservoirs; **c)** orifices; **d)** 1st stage pulse tube; **e)** 1st stage regenerator; **f)** 2nd stage pulse tube; **g)** 2nd stage regenerator

Predicted Cool Down Rates with no LN_2 Precooling (PTRs only)

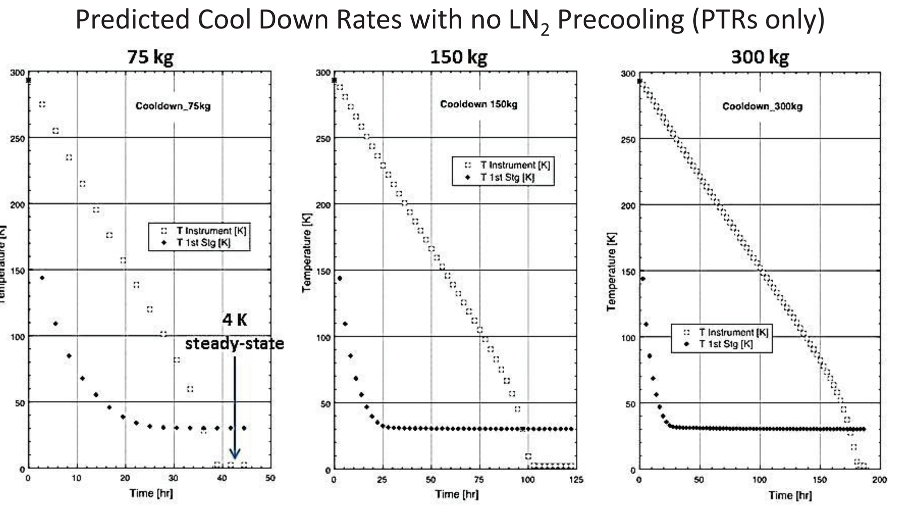

Figure 9-2 Cool down curves for a 75-, 150-, and 300kg cylinder of aluminum. This data suggests a LN_2 precooling may be favorable for more massive instruments. 9

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