# 阿波罗月球热流测量及其不确定性

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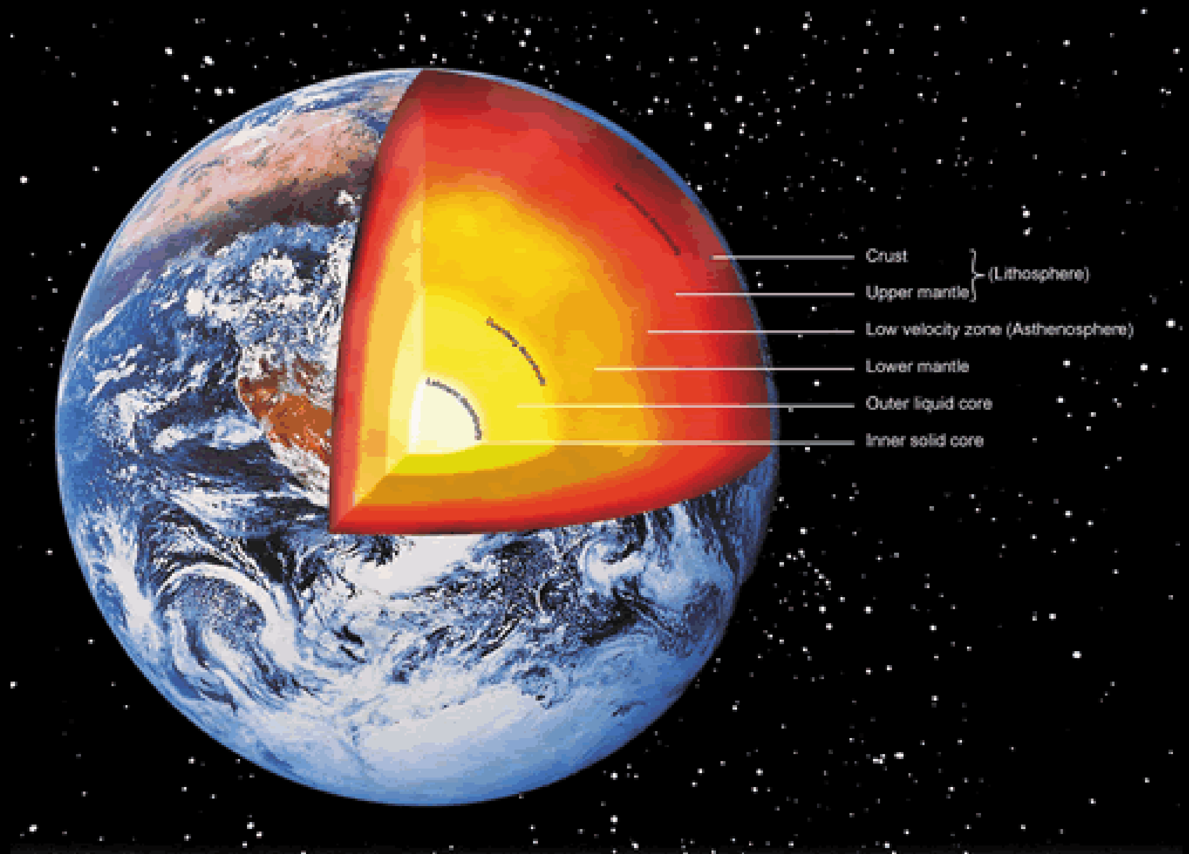
# 汇报内容

- 地球与月球热流测量方法
- 阿波罗热流实验及其结果
- 热流测量结果的不确定性

# 行星热流密度



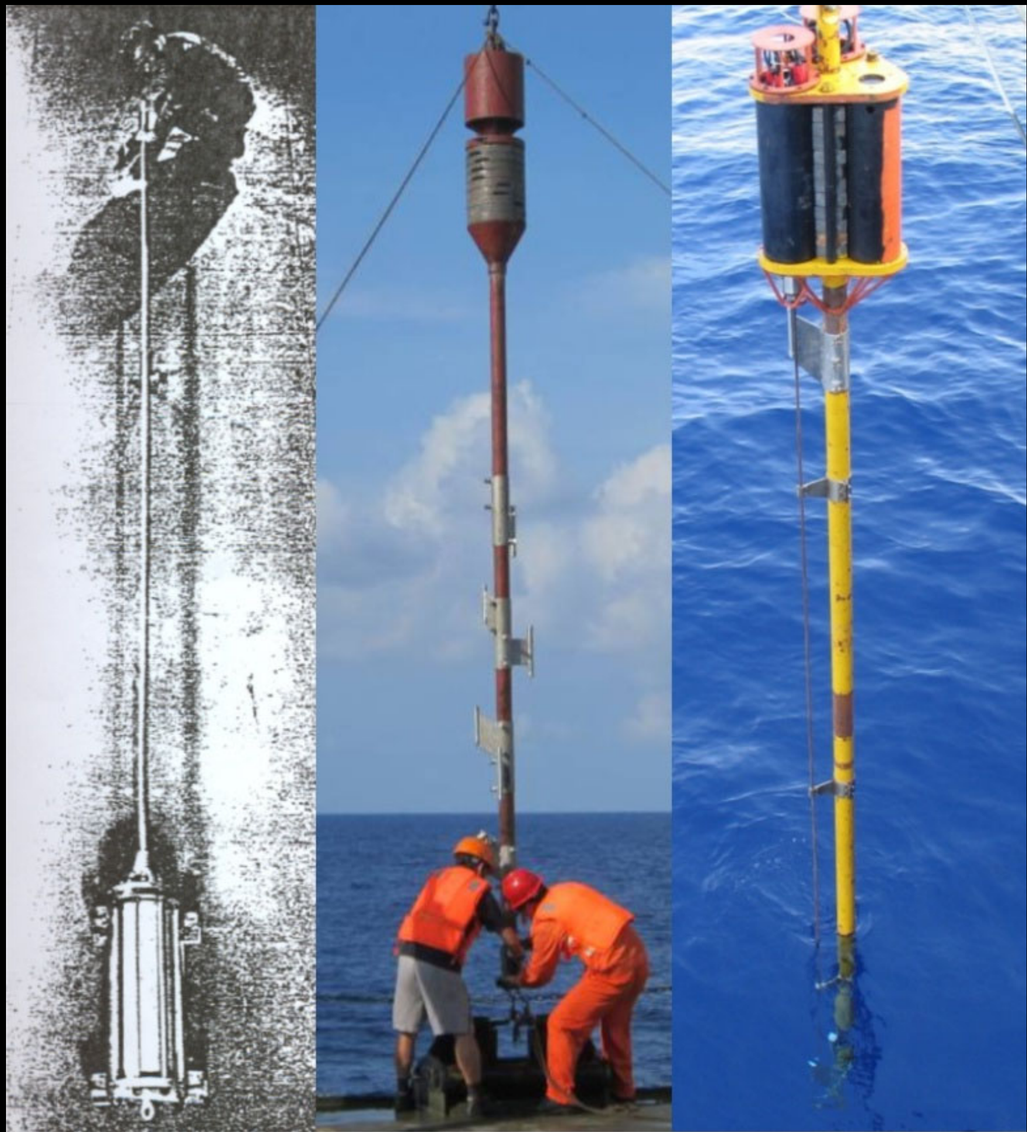

类地行星热流密度，简称热流，是指单位面积、单位时间内以由行星内部传输至表面的热量，是行星内部热状态和热结构在其表面最直接的显示。

# 陆地热流测量

热流密度 = 地温梯度 × 岩石热导率

×

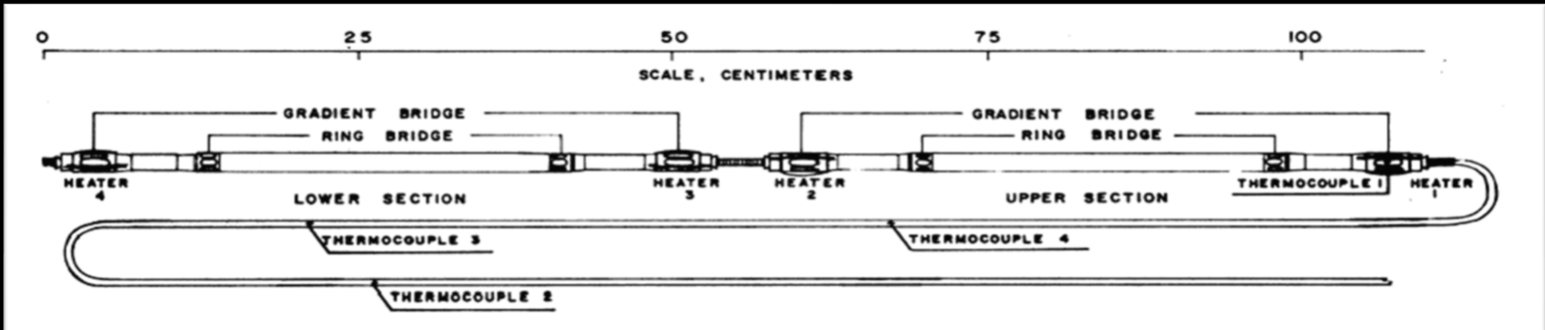
# 海底探针



南海所施小斌等

# 阿波罗热流探针

Langseth et al. 1972, The Moon




| Thermometer | Number and location | Temperature difference | | Absolute temperature | |
|---|---|---|---|---|---|
| | | Range, K | Accuracy, K | Range, K | Accuracy, K |
| Gradient bridge[a] | 1 per section, sensors separated by 47 cm | ±2 and ±20 | ±0.001 and ±0.01 | 190 to 270 | ±0.05 |
| Ring bridge | 1 per section, sensors separated by 28 cm | ±2 | ±0.002 | 190 to 270 | ±0.05 |
| Thermocouple | 4 per probe, in the first 2 m of the cable above probe | – | – | 70 to 400 | ±0.7 |
| Thermocouple reference bridge | 1 per experiment, mounted on radiation plate of electronics box | – | – | 253 to 363 | ±0.01 |

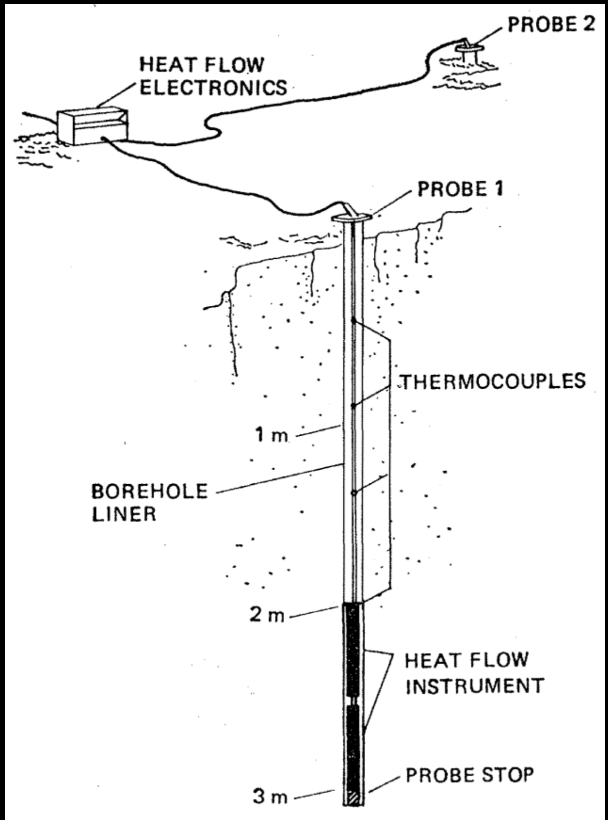
[a] Gradient bridge temperature difference measurements are made at two sensitivities with a ratio of 10 to 1.

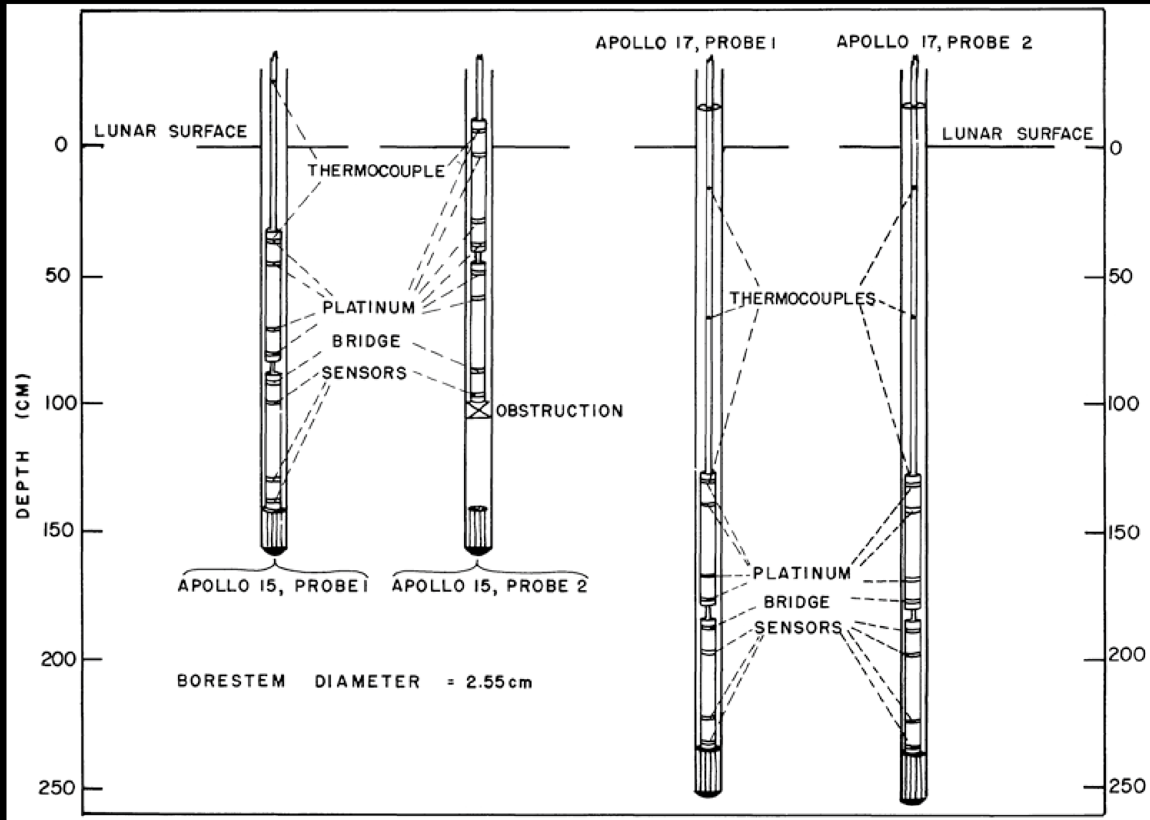
阿波罗月球热流实验是陆地钻孔与海洋探针方法的结合，形式上是陆地钻孔方法，实际测量却是探针方法。

# 阿波罗月球热流实验

Images credit:  NASA

# 阿波罗钻孔

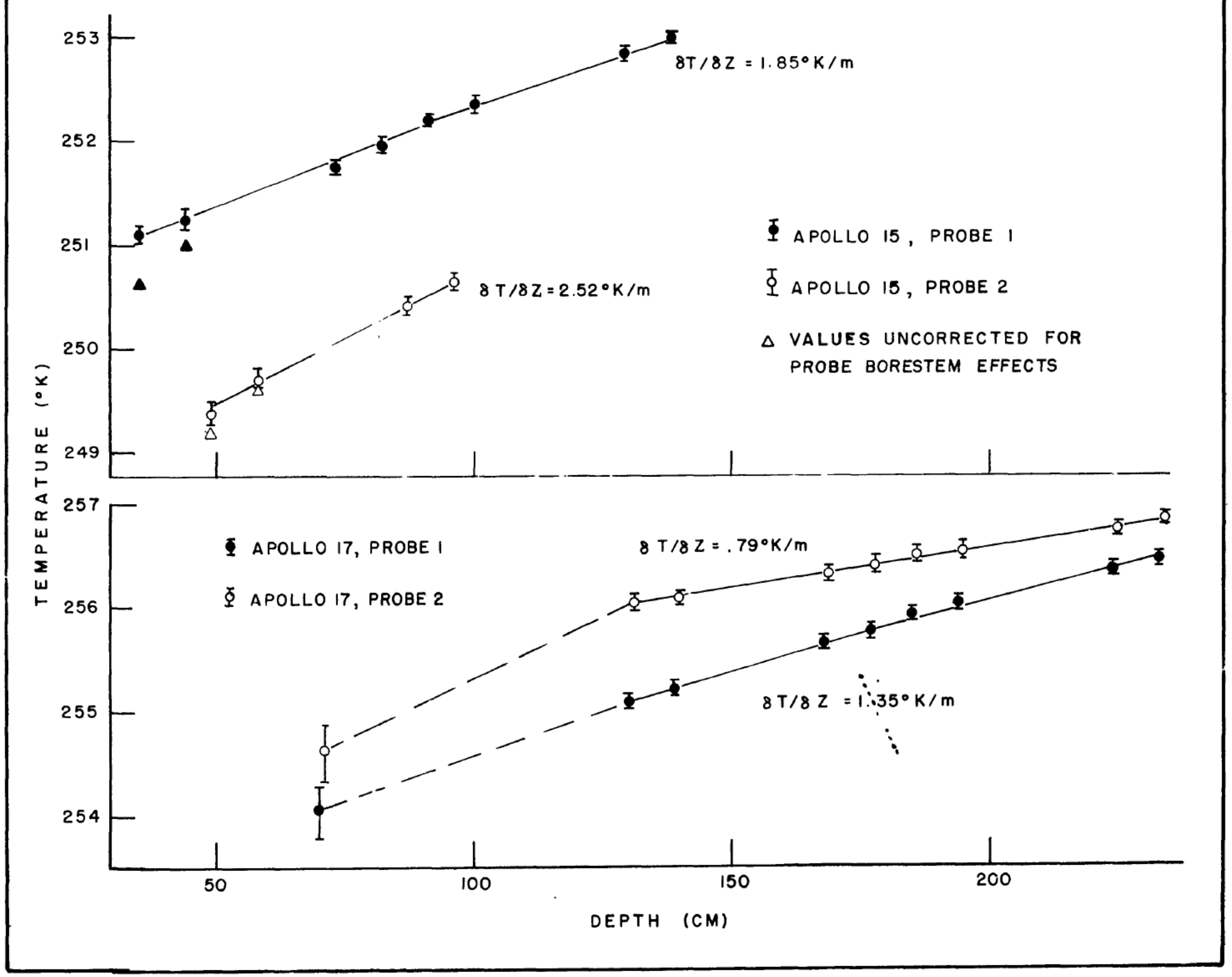


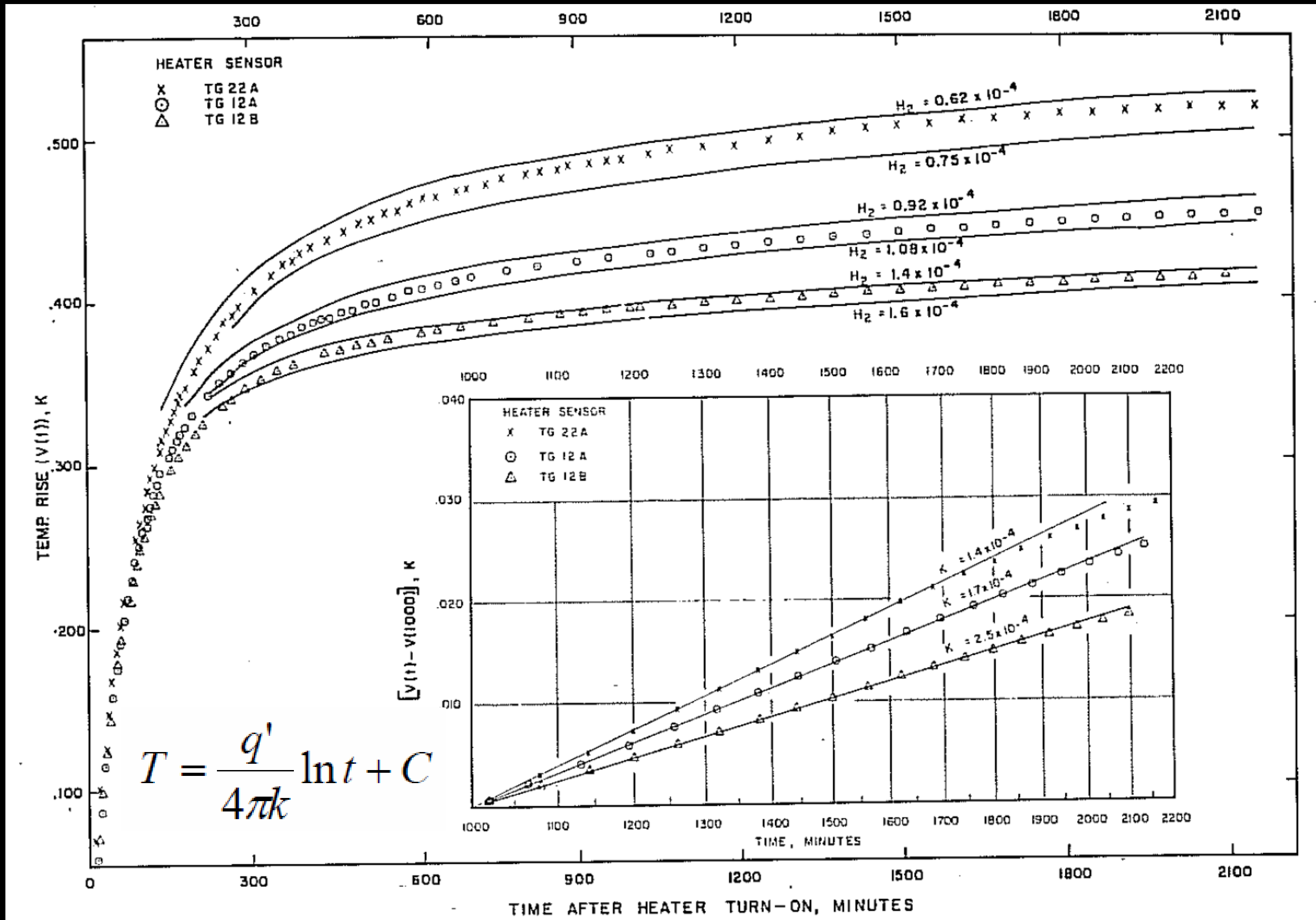

Langseth et al. 1970, Science; 1976, Proc. Lunar Sci. Conf.

# 温度-深度剖面

Langseth et al. 1976, Proc. Lunar Sci. Conf.



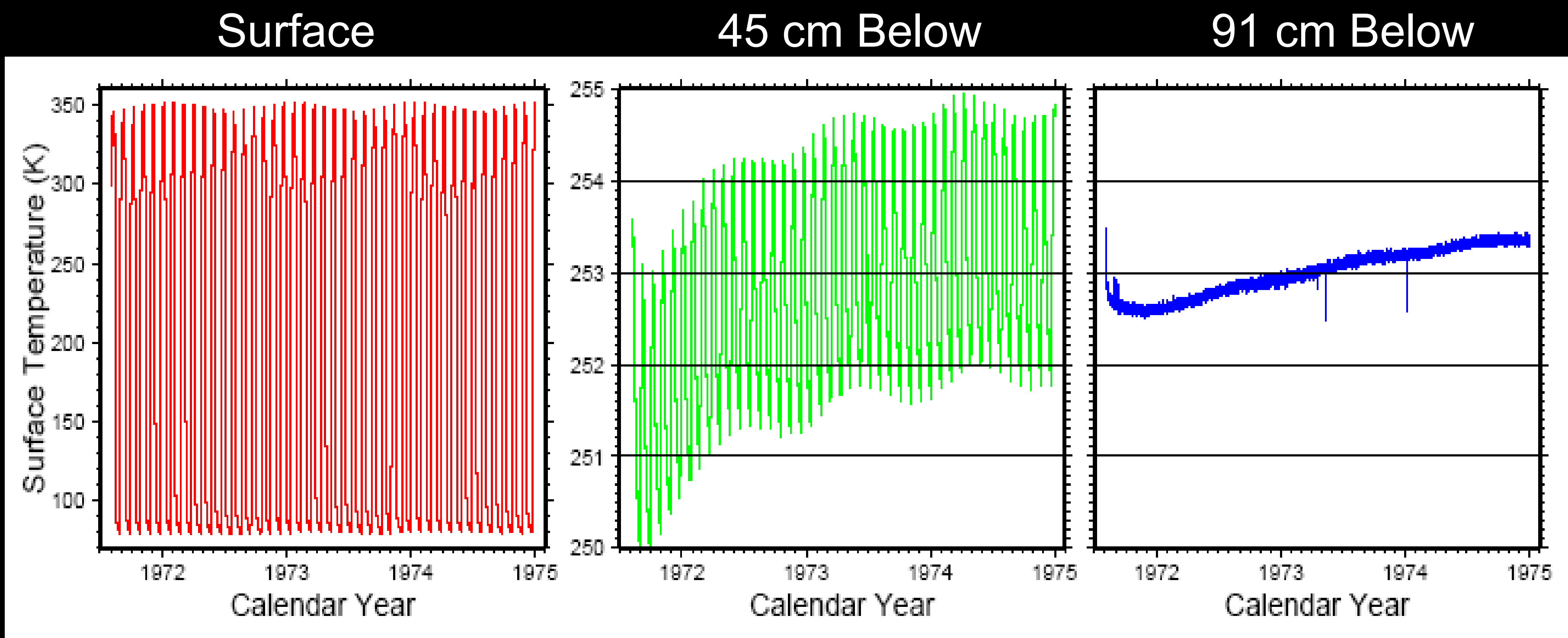
# 热导率测量点源热脉冲法




$$T = \frac{q'}{4\pi k}\ln t + C$$

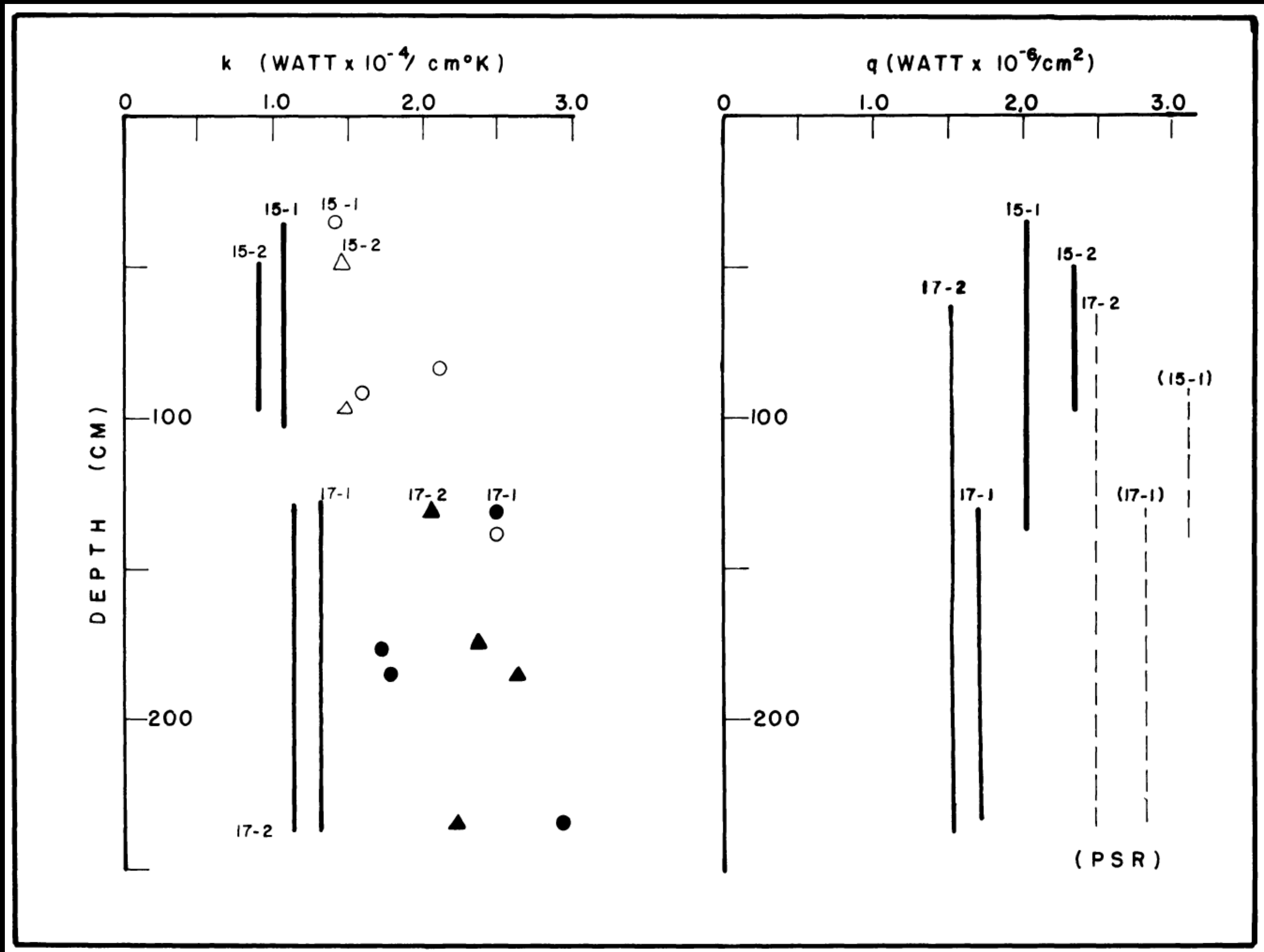
Langseth et al. 1976, Proc. Lunar Sci. Conf.

# 不同深度的温度系列




$$\Delta T(z,t) = Ae^{-z/\sqrt{\omega/2\lambda}} \cos(\omega t - z/\sqrt{\omega/2\lambda})$$

# 阿波罗两种热导率测量方法与热流



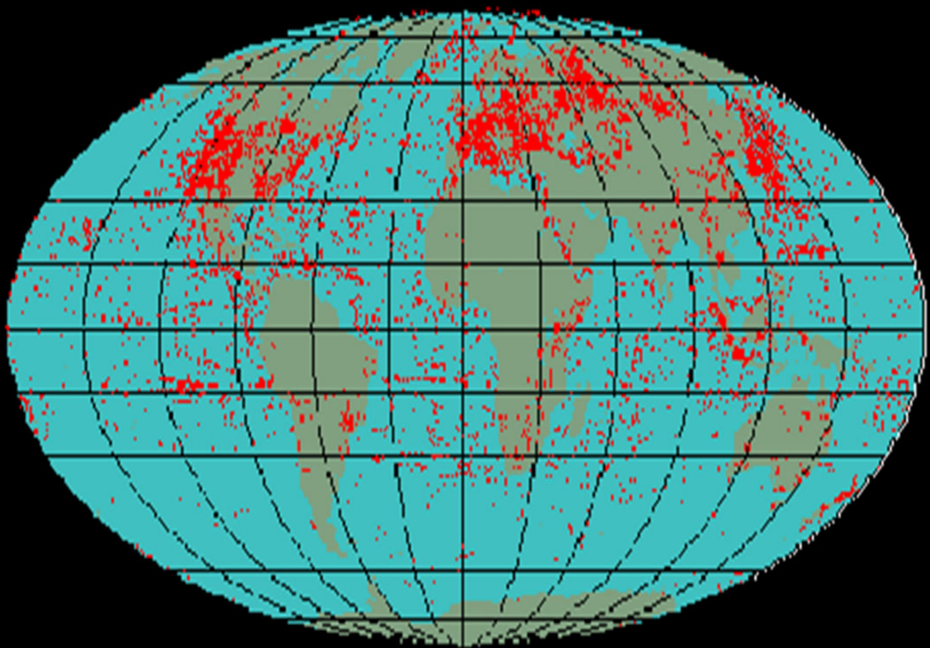

Langseth et al. 1976, Proc. Lunar Sci. Conf.

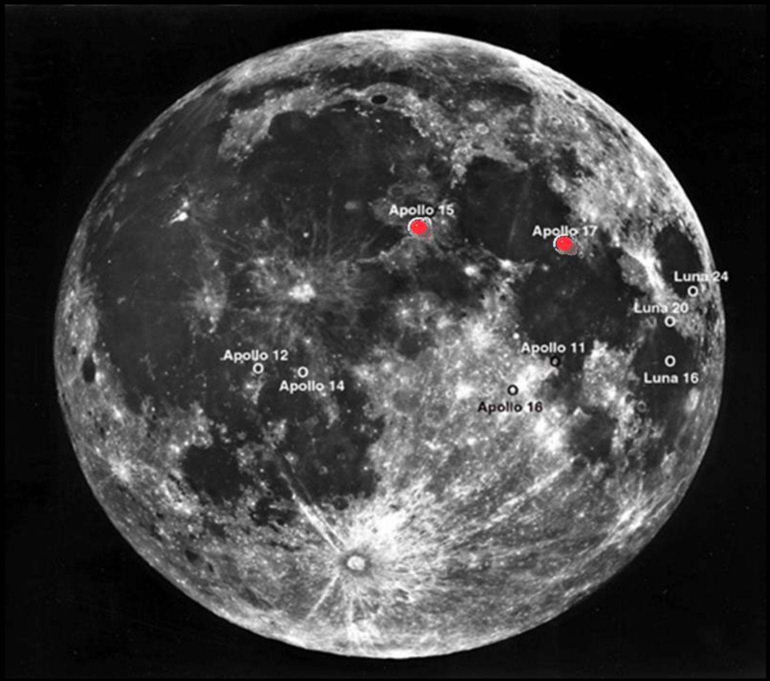
# 阿波罗热流实验的部分结果

| Datum | Hadley Rille | Taurus Littrow |
| --- | --- | --- |
| Thermal conductivity of the surface layer mW $m^{-1}$ $K^{-1}$ (at 120 K) ...................... | 1.2 ± 0.03 | 1.5 ± 0.03 |
| Average conductivity below 10 cm, mW $m^{-1}$ $K^{-1}$ .............. | 10 ± 10% | 15 ± 10% |
| Depth at which lunation fluctuations fall to 1% of surface value, m .................... | 0.29 | 0.33 |
| Depth at which annual fluctuation falls to 1% of surface value, m .................... | 1.35 | 1.48 |
| Mean vertical temperature gradient (most reliable probe), K/m ........................ | 1.85 | 1.35 |
| Observed surface heat flow, mW/$m^2$ | 21 | 16 |
| Correction applicable to the observed heat flow due to terrain, percent ........... | <4 | -10 |

NASA Report, *Apollo Program Summary Report*

# 地球与月球热流测点分布





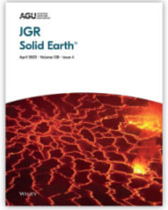

地球热流测点超过5万个，迄今月球仅有2个

# 高估了?

JGR Solid Earth

Megaregolith insulation, internal temperatures, and bulk uranium content of the moon

Paul H. Warren, Kaare L. Rasmussen




Volume 92, Issue B5
10 April 1987
Pages 3453-3465

**……，our best estimate for global mean heat flow is 12 mW $m^{-2}$.**

*Geophysical Constraints on the Lunar Interior*

L. L. HOOD

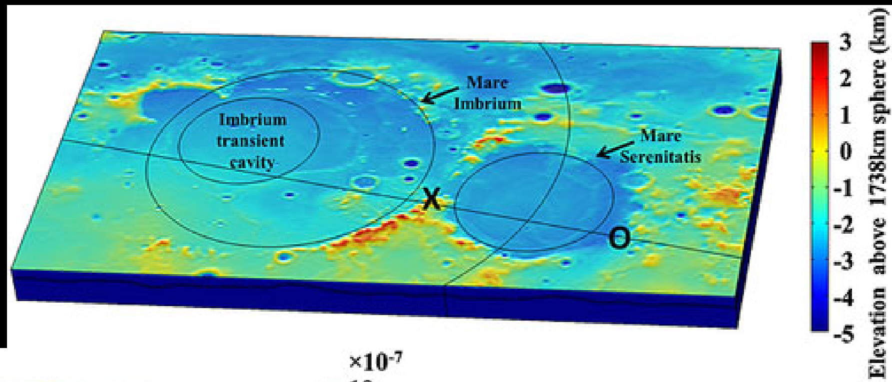
*Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721*

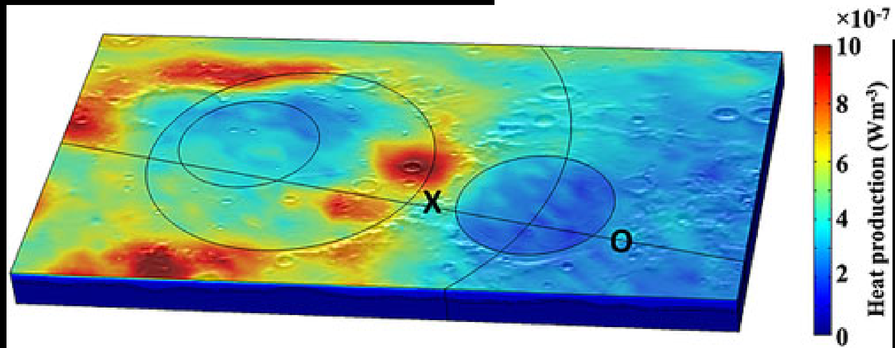
**……，mean surface rates of 11 and 18 mW/$m^2$ would imply bulk Moon uranium abundances of 29 and 46 ppb, respectively, compared to 14 ppb for CI chondrites and 18 ppb for the bulk Earth.**

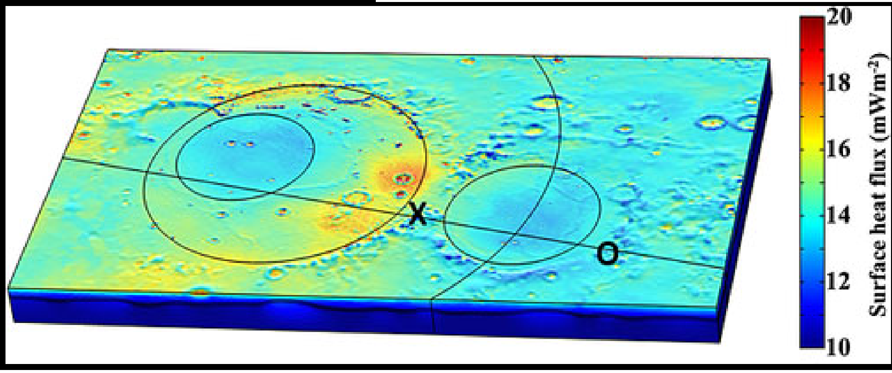
# 正合适?

**Lunar heat flow: Regional prospective of the Apollo landing sites**

M. A. Siegler[1] and S. E. Smrekar[1] JOURNAL OF GEOPHYSICAL RESEARCH: PLANETS, VOL. 119, 47–63,

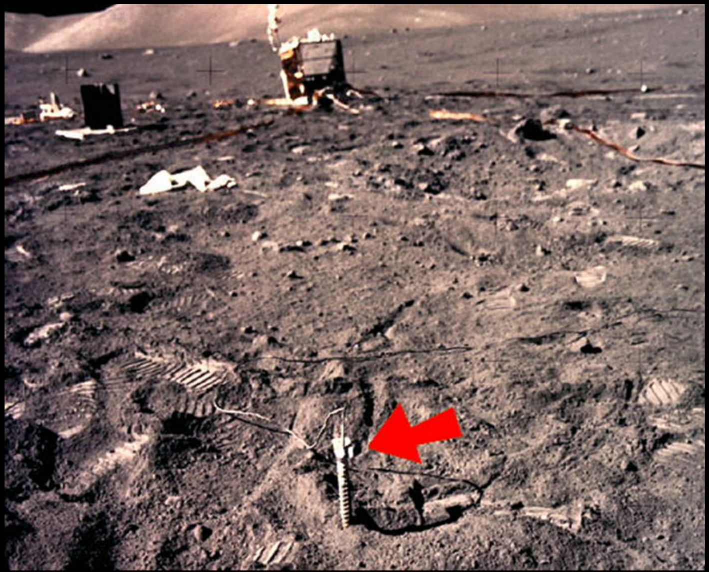


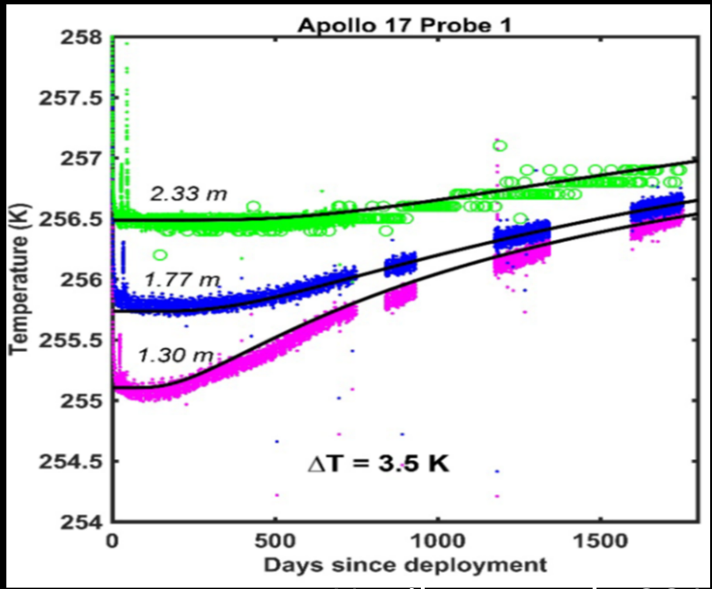




**a roughly 9–13 mW m$^{-2}$ mantle heat flux best approximate the observed heat flux.**

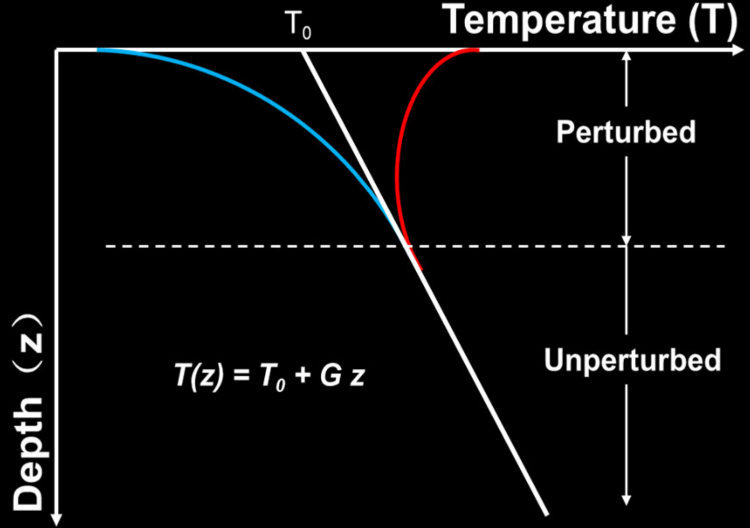
# 低估了?



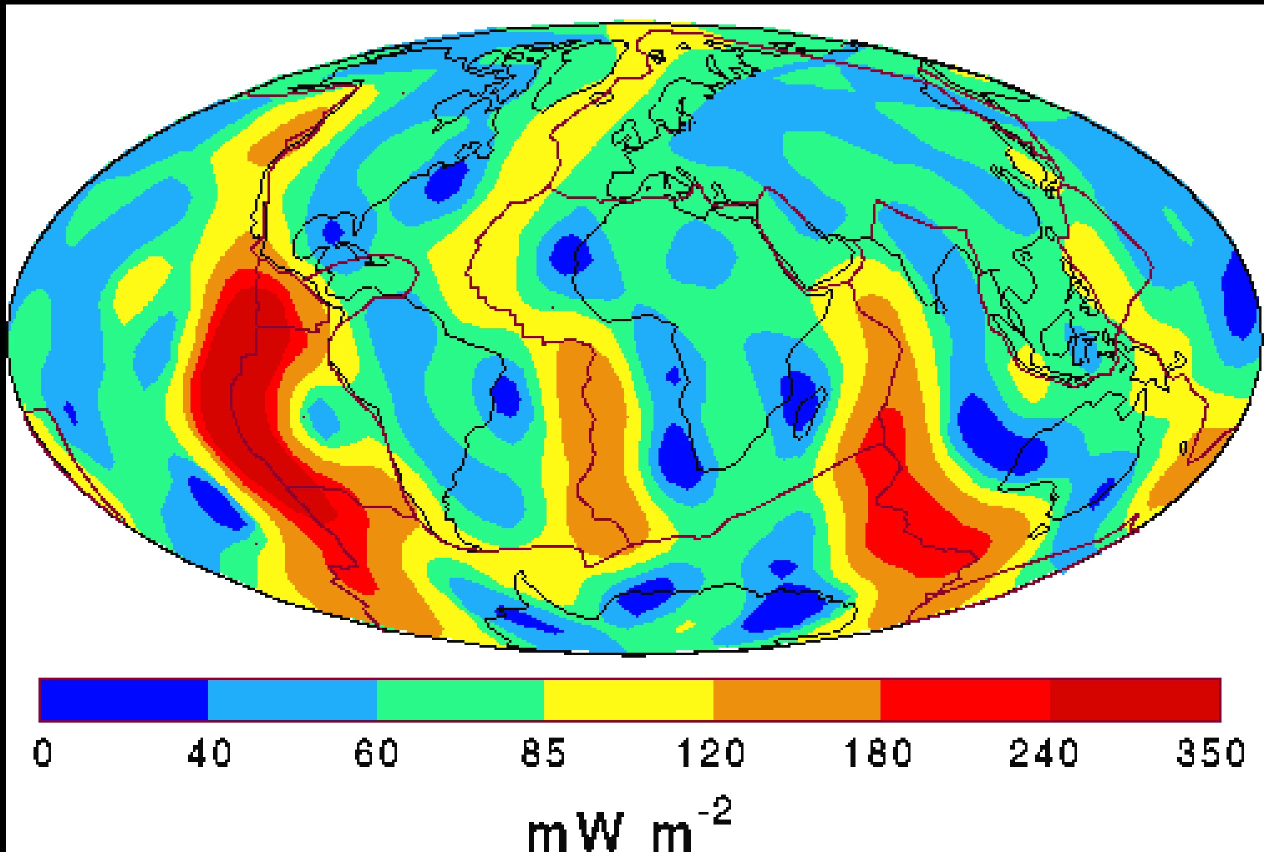
Credit: NASA




Nagihara et al., 2018

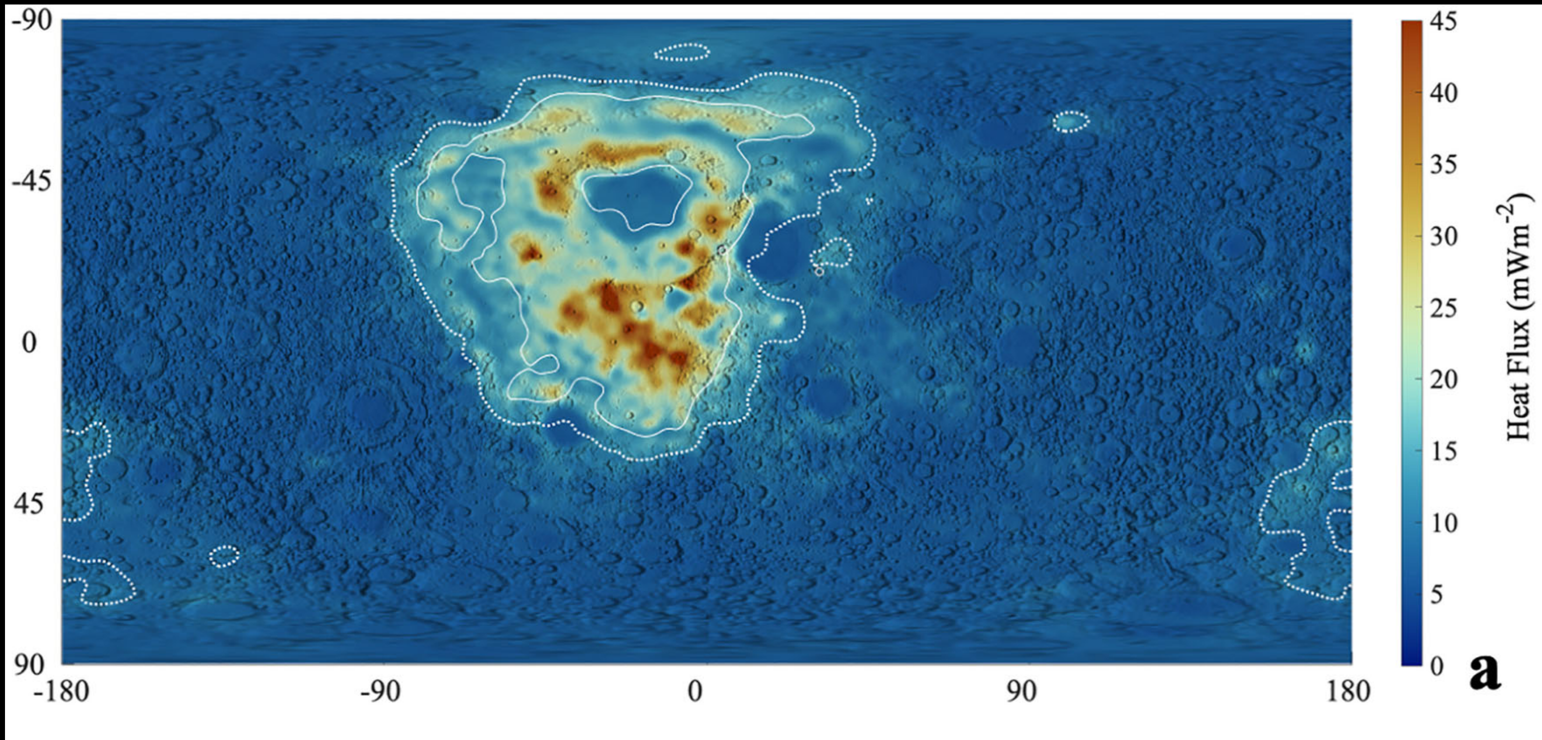


# 地球热流分布




地球能量输出**44.2TW (Pollack et al., 1993)**

# 月球热流分布




月球总能量输出**3.5 × $10^{11}$ W (Seigler et al., 2022)**

# 月球与地球内部热源

| | 月球 | 地球 |
|---|---|---|
| 总散热量($10^{12}$W) | 0.35 | 44.2 |
| 质量 ($10^{24}$kg) | 0.07342 | 5.972 |
| 生热散热比 | 0.93 | 0.6 |
| 总平均生热率（$10^{-12}$W/kg） | 4.43 | 4.44 |
| 表面积($10^{12}m^2$) | 37.93 | 510.07 |
| 平均热流密度($mW/m^2$) | 9.23 | 86.65 |

# 月球岩浆长期活动之谜

Article

## Two-billion-year-old volcanism on the Moon from Chang'e-5 basalts

https://doi.org/10.1038/s41586-021-04100-2
Received: 28 July 2021
Accepted: 6 October 2021

Qiu-Li Li[1,6], Qin Zhou[2,6], Yu Liu[1], Zhiyong Xiao[3], Yangting Lin[4], Jin-Hua Li[4], Hong-Xia Ma[1], Guo-Qiang Tang[1], Shun Guo[1], Xu Tang[4], Jiang-Yan Yuan[1], Jiao Li[1], Fu-Yuan Wu[1], Ziyuan Ouyang[5], Chunlai Li[2]✉ & Xian-Hua Li[1]✉

Article

## Non-KREEP origin for Chang'e-5 basalts in the Procellarum KREEP Terrane

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Published online: 19 October 2021

Heng-Ci Tian[1,4], Hao Wang[2,4], Yi Chen[2,4], Wei Yang[1]✉, Qin Zhou[3], Chi Zhang[1], Hong-Lei Lin[1], Chao Huang[2], Shi-Tou Wu[2], Li-Hui Jia[2], Lei Xu[2], Di Zhang[2], Xiao-Guang Li[2], Rui Chang[1], Yue-Heng Yang[2], Lie-Wen Xie[2], Dan-Ping Zhang[2], Guang-Liang Zhang[3], Sai-Hong Yang[3] & Fu-Yuan Wu[2]

Article

## A dry lunar mantle reservoir for young mare basalts of Chang'e-5

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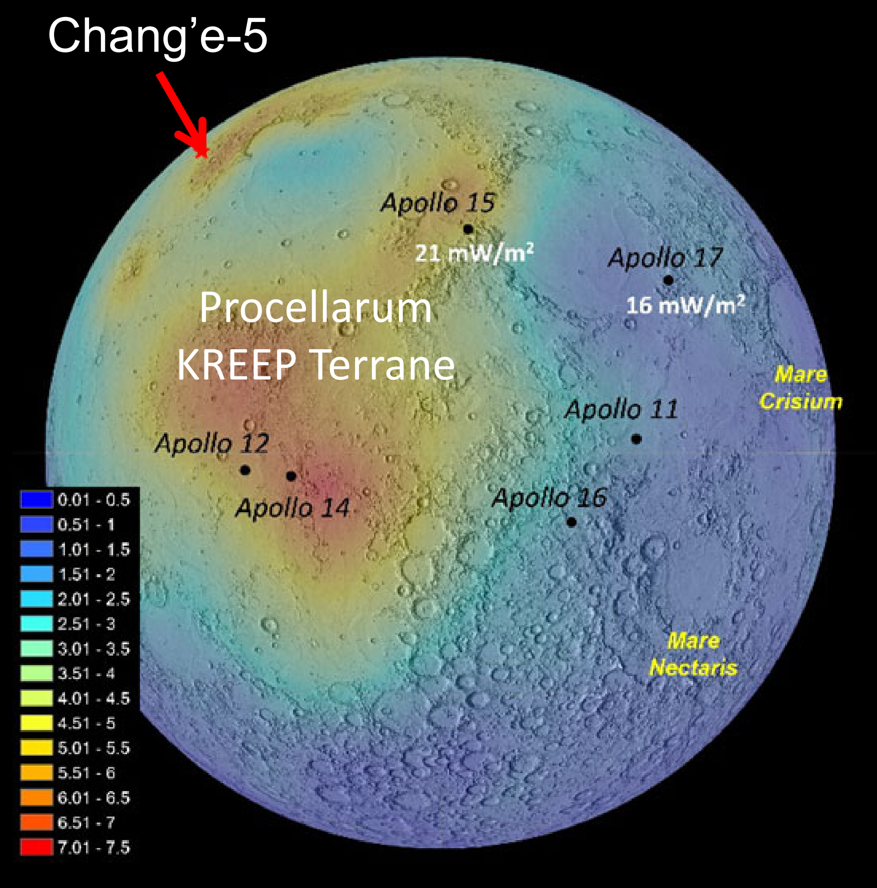
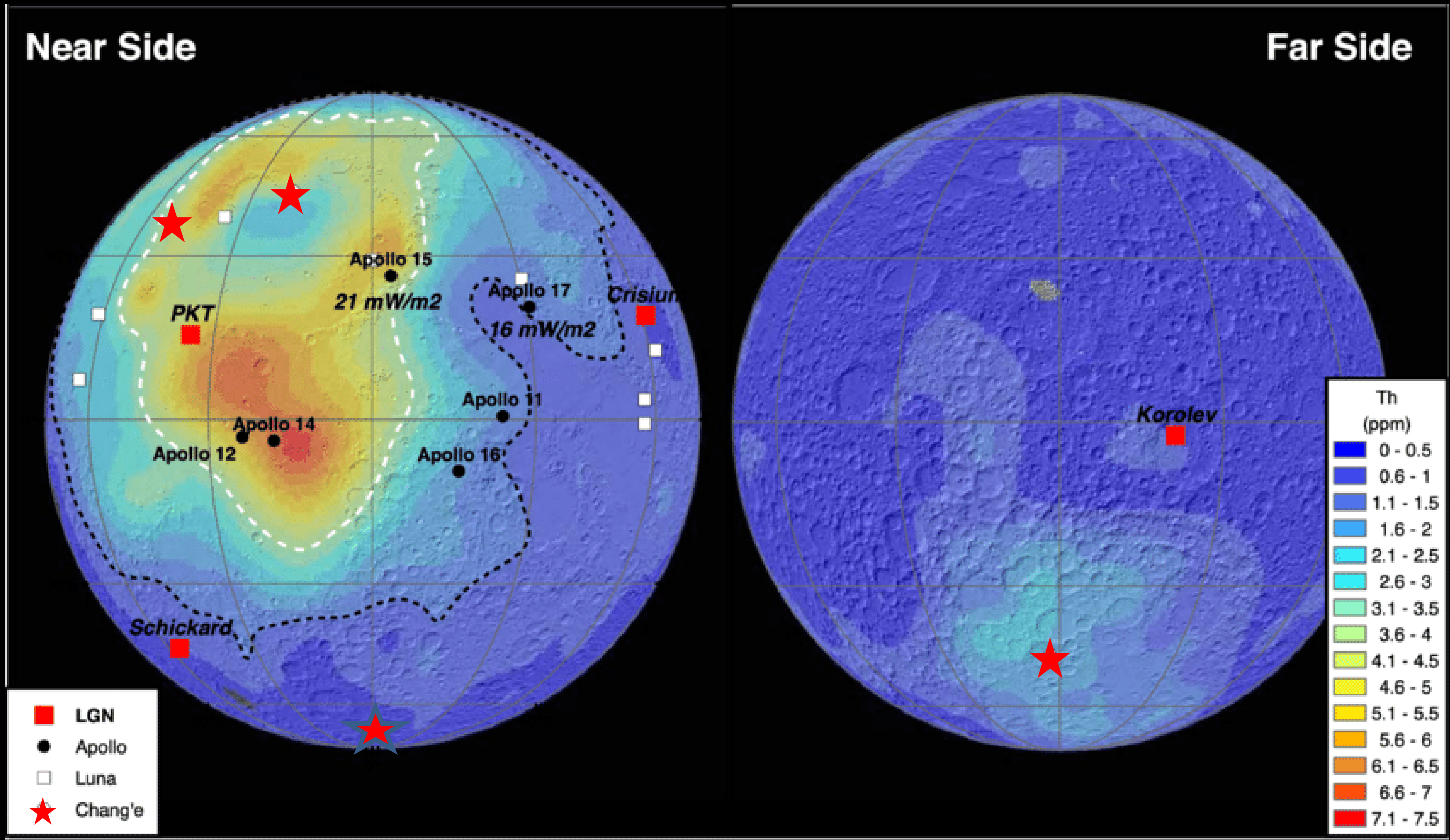
Sen Hu[1]✉, Huicun He[1], Jianglong Ji[1], Yangting Lin[1]✉, Hejiu Hui[2,3], Mahesh Anand[4,5], Romain Tartèse[6], Yihong Yan[1], Jialong Hao[1], Ruiying Li[1], Lixin Gu[1], Qian Guo[7], Huaiyu He[7] & Ziyuan Ouyang[8]




Th Map Based on Nagihara et al., 2018

# 月球物理网络点




据Haviland *et al* 2022 *Planet. Sci. J.* **3** 40

# 结束语

月球热流的分布规律和具有全球代表性的平均月球热流值对于研究月球的形成和演化具有至关重要的意义。但是任何热流测量都不可避免地受到测点特定地质和地理环境的影响。目前地球上热流测点超过**5**万个，而月球上仅有**2**个，远远不能满足月球科学研究的需要。新的月球热流测量应该成为将来月球探测科学任务的重中之重。


# 敬请批评指正

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