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DEEP IMAGING OF THE FIELD OF THE $z = 4.9$ QUASAR PC 1247+3406, AND FAINT GALAXY COUNTS IN THE K BAND WITH THE KECK TELESCOPE[1]

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ABSTRACT

We present deep images in the K_s band of the field of the quasar PC 1247+3406 at $z = 4.897$, obtained using the near-infrared camera on the W. M. Keck telescope. A number of faint sources have been detected, some of which appear to be quite red. Their nature and redshifts remain uncertain at this time. These data are combined with deep Keck infrared images of five additional fields and present galaxy counts reaching down to $K_s = 22$ mag, comparable to the deepest K-band surveys to date. The data presented here are in good agreement with the Hawaii Deep Survey and represent the first independent verification of those results. The slope of the log N–log S relation derived from these data agrees well with the Hawaii Deep Survey, while the counts are slightly higher, especially at the faintest levels probed here. This may be due to a presence of groups or clusters around the target objects at high redshifts.

Subject headings: cosmology: observations — galaxies: general — quasars: individual (PC 1247+3406)

1. INTRODUCTION

One of the basic experiments which can be used to probe the evolution of galaxies, and possibly the global geometry, is the counts of faint galaxies. Here we present the first data obtained that address these problems using the W. M. Keck telescope. These data illustrate the power of the Keck telescope in attacking the problems of observational cosmology.

In the last few years, evolution effects have been clearly established from the slopes and intercepts of galaxy counts as a function of magnitude in bandpasses ranging from B to K. One of the more interesting results, which is still not fully understood, is the existence of an apparent excess of faint galaxies at $B > 23$ mag, many of which appear to be actively star-forming, low-luminosity systems at moderate redshifts ($z \sim 0.3$–0.5). The evidence for this excess is less prominent in the K-band galaxy counts, possibly because this wavelength should be less affected by star formation. More details can be found, for example, in the papers by Lilly, Cowie, & Gardner (1991), Cowie, Songaila, & Hu (1991), Cowie et al. (1993), Broadhurst, Ellis, & Glazebrook (1992), Lilly (1993), Colless et al. (1993), and Gardner, Cowie, & Wainscoat (1993) and in the recent reviews by Koo & Kron (1992), Ellis (1993), and Cowie & Songaila (1993), and references therein.

In addition to unbiased field surveys, *targeted* surveys centered on the known high-redshift objects, for example, radio galaxies or quasars, are of some interest, since such objects may well mark the sites of galaxy (proto)clusters, or even regions of enhanced galaxy formation (see Smith, Thompson, & Djorgovski 1993). Here we present a preliminary analysis of deep infrared imaging of the field of PC 1247+3406, a quasar at $z = 4.897$ (Schneider, & Schmidt, & Gunn 1991), currently the most distant object known, as well as number counts from this field and other fields observed in the infrared on the W. M. Keck telescope.

2. OBSERVATIONS AND DATA REDUCTION

The infrared data used in this paper consist of images of six fields taken in the K_s(1.99–2.32 μm) band with the near-infrared camera (NIRC) on the 10 m W. M. Keck telescope on Mauna Kea during the scientific demonstration observations in 1993 March. The camera uses a 256 × 256 element InSb array with a scale size of 0".15 pixel^{-1} giving a total field 38".4 × 38".4. A detailed description of the camera is given in Matthews & Soifer (1993), and the data reduction is described in Matthews et al. (1993).

Keck observations of the PC 1247+3406 field were obtained on the nights of UT 1993 March 24 and 25. Images of some of the other fields are discussed in companion papers (Matthews et al. 1993; Graham et al. 1993; Larkin et al. 1993). The details of the individual fields are given in Table 1. Magnitude zero-point calibrations were obtained from observations of three faint standard stars, M13-A14, G162-66, and G136-50 (Casali & Hawarden 1992). We estimate the overall zero-point uncertainty to be $\simeq 0.06$ mag. The limiting magnitude near the center of the stacked image is $K_s \simeq 22.0$ mag, while the seeing is FWHM $\simeq$ 0".8.

We supplemented the infrared data with deep images of PC 1247+3406 in the visible, obtained using the 4-shooter imager on the Palomar 200 inch (5 m) Hale telescope. The data were obtained in the Gunn-Thuan *gri* bands on the nights of UT 1992 March 30 and April 30. Multiple exposures were registered and co-added, in each band. The estimated limiting magnitudes ($\simeq 2\ \sigma$) in the final images are $g \simeq 25$ mag, $r \simeq 25.5$ mag, and $i \simeq 25$ mag, and the seeing was in the range of FWHM $\simeq$ 0".8–1".3. The data were processed using standard techniques. The magnitude zero points were determined from the quasar itself, using data from Schneider et al. (1991); we

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TABLE 1

Deep Fields Observed at K_S

Field	Galactic Latitude (b)	t_{int} (s)	3.5 σ K_S Magnitude Limit	Number[a] Observed	Number[a] Observed–Spurious	Field area (arcmin^2)
PC 1247+3406	83	2200	21.5	20	17.5	1461.6
4C 41.17	17	2400	21.5	13	11.1	1204.7
FSC 10214+4724	55	1400	22.0	32	28.4	1343.9
Q1634+267	40	970	21.3	9	8.9	1143.9
B1422+231	69	550	20.2	6	6.0	1394.1
MG 1131+0456	61	270	20.6	18	17.9	1403.8

[a] Since binning was done in half magnitude bins, the numbers are for objects brighter than nearest half magnitude above 3.5 σ limit. Counts exclude central targets and surrounding masked areas.

estimate the net zero-point uncertainties to be $\simeq 0.2$ mag, and we have included those with the measurement uncertainties for faint objects, discussed below. This zero-point uncertainty probably dominates over the errors due to the possible variability of the quasar itself.

3. THE FIELD OF PC 1247+3406

The quasar PC 1247+3406 at $z = 4.897$ is a natural target for deep cosmological observations. The first objects on galaxy scales which collapsed in the early universe, of which this is a plausible example, may mark favored sites of early galaxy formation (Djorgovski, Smith, & Thompson 1991; Smith et al. 1993). Our observations were partly motivated by the possibility of detecting a protocluster at $z \simeq 5$.

The stacked NIRC K_s-band image of the field is shown in Figure 1 (Plate L1), with a number of detected objects marked. The images in the four bands available ($griK_s$) are shown in Figure 2, and the magnitudes of objects in all bands (following the numbering as in Fig. 1) are listed in Table 2. There is obviously a range of colors, as shown in the color-magnitude

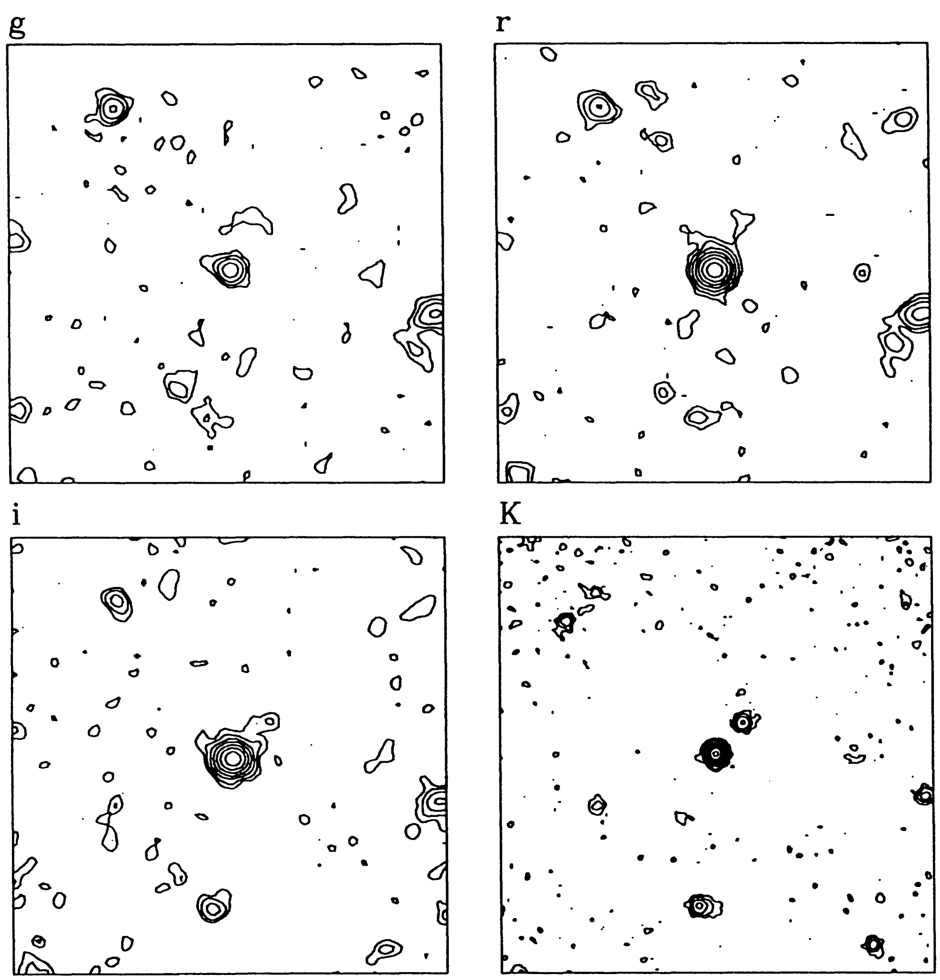

Fig. 2.—Intensity contour maps of the PC 1247+3406 field, in four bands ($griK_s$), as indicated. The field size is 38".4 × 38".4, with N at the top and E to the left. This illustrates the range of colors seen among the faint galaxies.

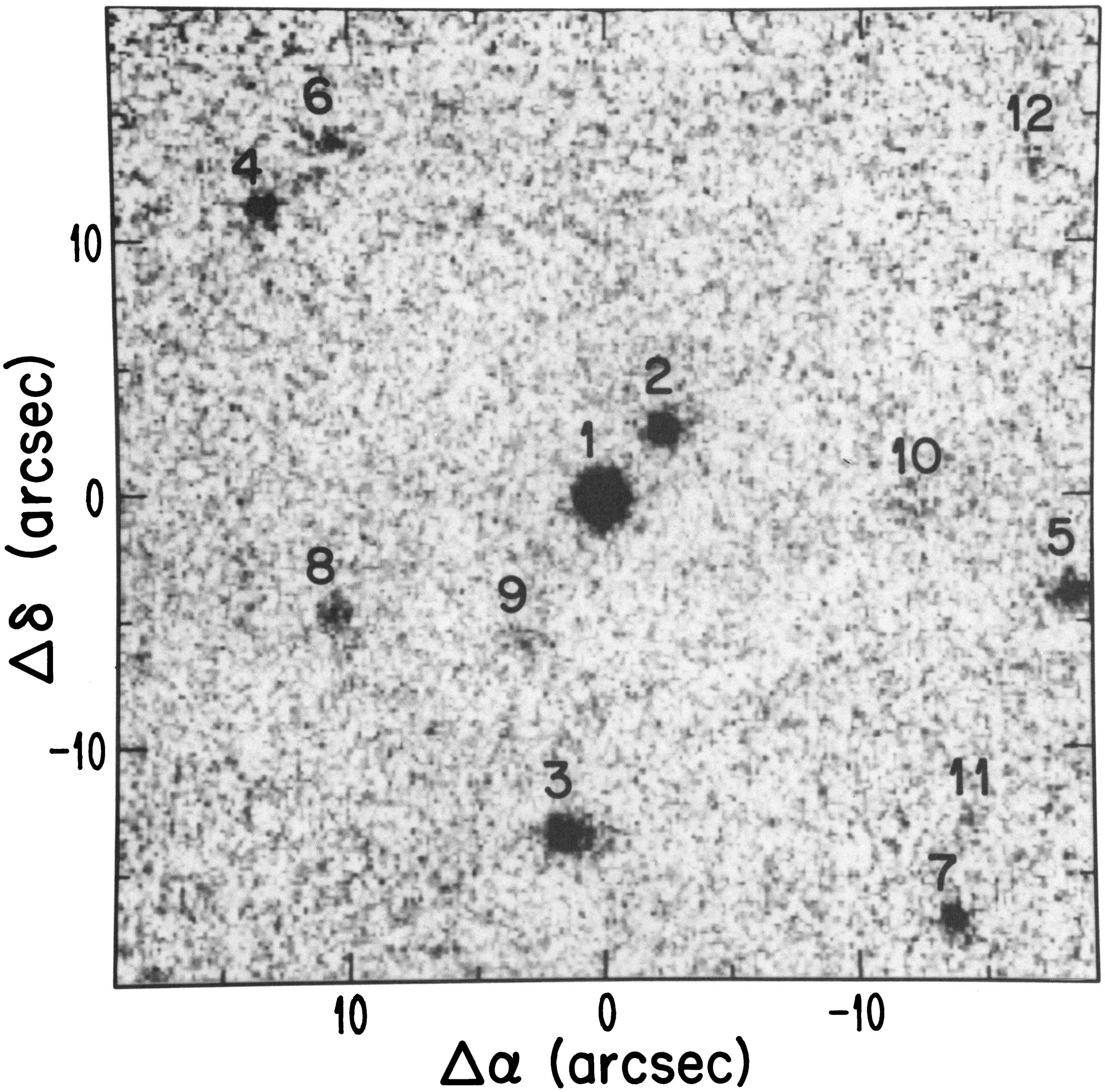

FIG. 1.—Stack image of the PC 1247+3406 field, in the K_s band, obtained at the W. M. Keck telescope. The field size is 38″.4 × 38″.4, with N at the top and E to the left. The 12 objects with the most significant detections are labeled, with no. 1 being the quasar itself.

SOIFER et al. (see 420, L2)

TABLE 2

MAGNITUDES OF OBJECTS IN PC 1247+3406 FIELD

Object	g	r	i	K_s
1 (QSO)	22.4	20.4	19.5	17.2
2	24.7	25.0	23.3	19.0
3	24.1	24.2	22.5	19.0
4	>26.3	>26.3	>25.3	19.7
5	22.4	22.5	21.9	19.7
6	22.7	23.0	22.7	20.4
7	>26.3	>26.3	23.2	19.8
8	>26.3	24.9	24.6	20.3
9	>26.3	24.5	24.3	20.8
10	24.5	24.7	23.9	21.3
11	>26.3	>26.3	>25.3	21.4
12	>26.3	24.1	23.4	21.0

diagrams of Figure 3. Objects are detected in the K_s image that are undetected in the *gri* frames, and therefore the lower limits on their $(i - K_s)$ and $(r - K_s)$ colors, are unconstrained by these data.

There is great similarity between the color-magnitude diagram of Figure 3 and the data presented by Cowie et al. (1993). Some of the objects found are comparable in color to the reddest objects seen by Cowie et al. In particular, a red extended object, presumably a galaxy, is seen within 3".6 NW of the quasar, that is, $\simeq 12$–$25\ h^{-1}$ kpc in projection at the quasar redshift, for $\Omega_0 \sim 1$–0. It has a magnitude $K_s = 19.4$ mag, and colors $(i - K_s) = 4.1$ mag ($[I - K_s] = 3.4$ mag in the Kron-Cousins system) and $(r - K_s) > 5.5$ mag. Its redshift is unknown at present. It may be a reddened actively star-forming young galaxy companion of the quasar. If this were the case, its rest-frame visible luminosity would be comparable to, or higher than, that of the most luminous starbursts now known: with the distance moduli of the order of $(m - M) \sim 48.2 \pm 1$ mag for $H_0 = 75$ km s^{-1} Mpc^{-1} and $\Omega_0 \sim 1$–0, $L_B \sim 10^{13}\ L_\odot$. While this may appear a priori unlikely, Matthews et al. (1993) have shown that a starburst of comparable luminosity is occurring in the *IRAS* source FSC 10214+4724. Another, perhaps more likely, possibility is that this is a more normal galaxy at a much lower redshift. Clearly, spectroscopy is needed before more can be said about it.

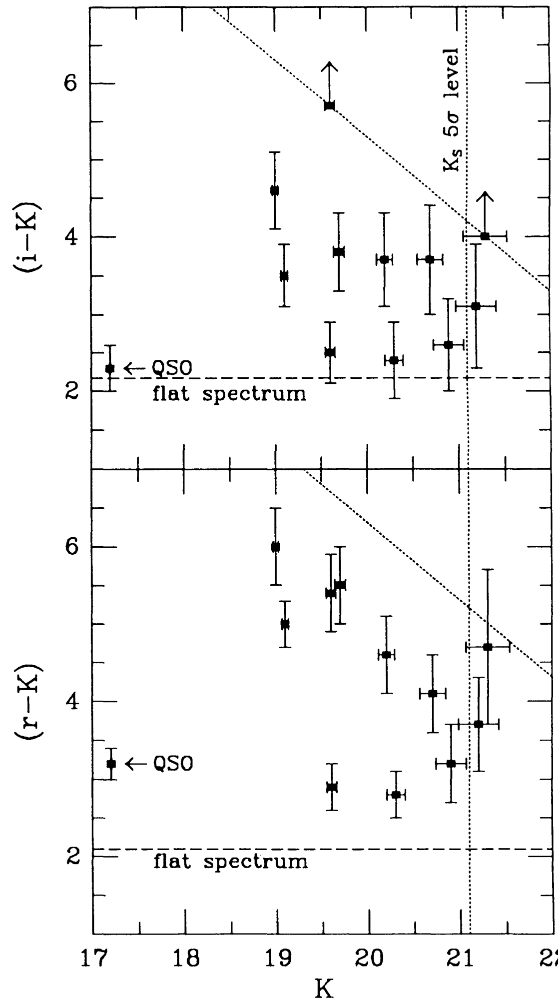

FIG. 3.—Colors of the objects detected in the PC 1247+3406 field, listed in Table 1. The lines corresponding to the magnitude limits are shown. For comparison to the data of Cowie et al. (1993) $(i - I) = 0.7$ mag, so the reddest objects in both data sets have very similar colors. Colors of objects range from those corresponding to a flat F_ν spectrum (as appropriate, e.g., for galaxies powered by active star formation) to objects detected only in the K_s images.

4. DEEP GALAXY COUNTS AT K_s

The targeted observations of Table 1 were used to obtain deep galaxy counts at 2 μm in the six fields listed above. The first step in object detection was to clip the final mosaiced fields to the central 38" × 38" which had the deepest and most uniform coverage. The target objects and an area around the target were then masked off. A bright star in each field was chosen as the point-spread function (PSF) and was convolved with the image to determine the detection limits of the field. The 1 σ detection level was calculated from the standard deviation of the convolved image over regions which had no obvious sources. Objects were defined as those regions with a 3.5 σ or greater level in the convolved image. The 3.5 σ limits calculated in this way are listed in Table 1. Based on simulations we believe that our counts are essentially 100% complete at this level, and thus no completeness corrections were made to our counts. To measure the total magnitudes of the detected sources, a 3" aperture was used and was corrected to the total flux by measuring the total flux for the bright, isolated objects in each field. The total solid angle used for the counts and the number of detected field objects in each image are listed for each field in Table 1. Also included in Table 1 is the number of sources corrected for possible spurious events. The rate of detection of spurious objects was determined in a statistical manner by convolving each PSF with a blank field with Gaussian noise and counting the number of spurious events per NIRC field in each detection bin.

The total counts for the six fields are shown in Figure 4, along with the completeness-corrected counts taken from Cowie et al. (1993). Cowie et al. quote counts reaching a magnitude deeper, but the completeness corrections are large at that point and are based on only a part of a single deep field (L. Cowie 1993, private communication).

The counts from the Keck images are in good agreement with those of Cowie et al. (1993) and represent the first independent check on these very important results from the Hawaii Deep Survey. The counts presented here are not corrected for stars; however Cowie et al. find that over the brightness range sampled here less than 10% of the objects are stars and are therefore a negligible effect in the comparison. There is excellent agreement between the slopes of the log N–log S counts in

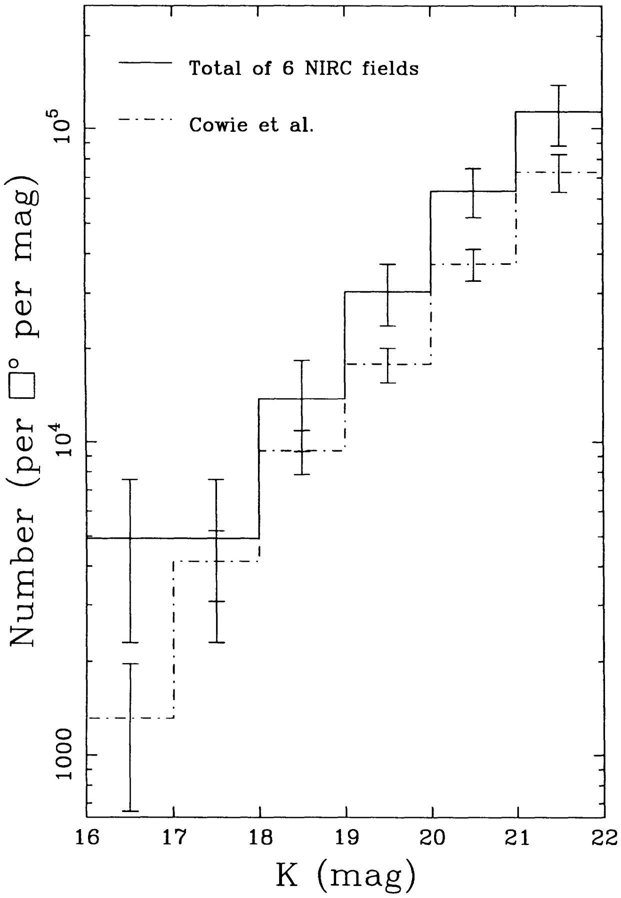

FIG. 4.—Number counts of objects for the six fields from our data (*solid line*), per square degree and per magnitude. Poissonian error bars are indicated for each bin. Counts from the Hawaii Deep Survey (Cowie et al. 1993) are shown for comparison (*dashed line*).

the present data and in the Hawaii Deep Survey. Our counts tend to be higher, with the largest deviation in the brightest magnitude bin. This is probably due to our inability to reject foreground stars on the basis of colors, and the small numbers of bright objects in our data. The apparent excess in the faint bins is more intriguing, but it must be emphasized that the fields observed were targeted on a priori known high-redshift objects, which may well reside in groups or clusters.

5. CONCLUDING REMARKS

The counts presented here were done in a simple way that makes negligible the effects of modeling of noise sources, and our basic result is that the preliminary faint galaxy counts in the K_s band agree to within the Poissonian errors with the counts presented earlier by other groups, notably Cowie, Gardner, and their collaborators. We see variations in numbers of objects from field to field, which may well reflect large-scale structure at a great depth, but the numbers are still too small to make any firm conclusions at this point. The relatively high number of objects in the PC 1247+3406 and FSC 10214+4724 fields, as well as the large number of sources immediately surrounding 4C 41.17 (Graham et al. 1993), is intriguing but falls short of evidence for clusters. Deeper images and control fields, as well as spectroscopic observations, are needed to test this possibility.

We also see hints of a population of numerous faint *red* galaxies. Their nature will have to be resolved by follow-up spectroscopy. Given the lack of evidence for an obvious population of protogalaxies in deep searches in the visible (see Djorgovski, Thompson, & Smith 1993 and references therein), this raises the intriguing possibility that such a population may make its appearance in the near-infrared, at the flux levels we are now beginning to explore.

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