Assembled Kinetic Impactor (AKI) for Deflecting Asteroids via Combining Spacecraft with Launch Vehicle Upper Stage

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7th IAA Planetary Defense Conference
VIENNA, AUSTRIA
April 2021

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1 Research Backgrounds

Tunguska Event (1908)
50-m-diameter

2,000 square kilometers of forest were destroyed

Chelyabinsk Event (2013)
20-m-diameter

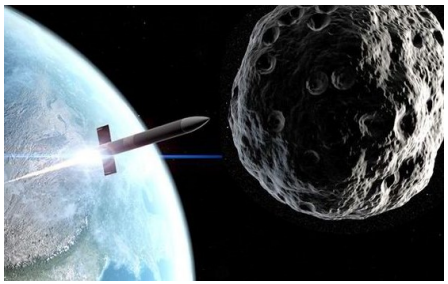
1500 people were injured, 3,000 houses were damaged

2019 OK (2019-7-25)
60-m-diameter

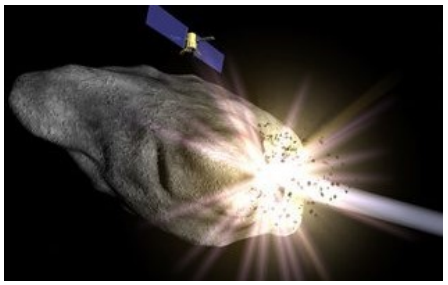
Flyby Earth at a height of 65,000 km

1 Research Backgrounds

Bunker

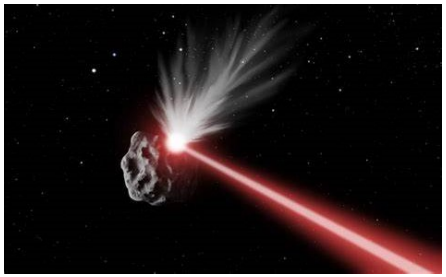


Nuclear Explosion



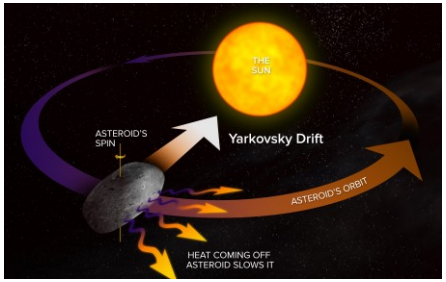
Kinetic Impactor

Laser Ablation



Gravitational Tractor

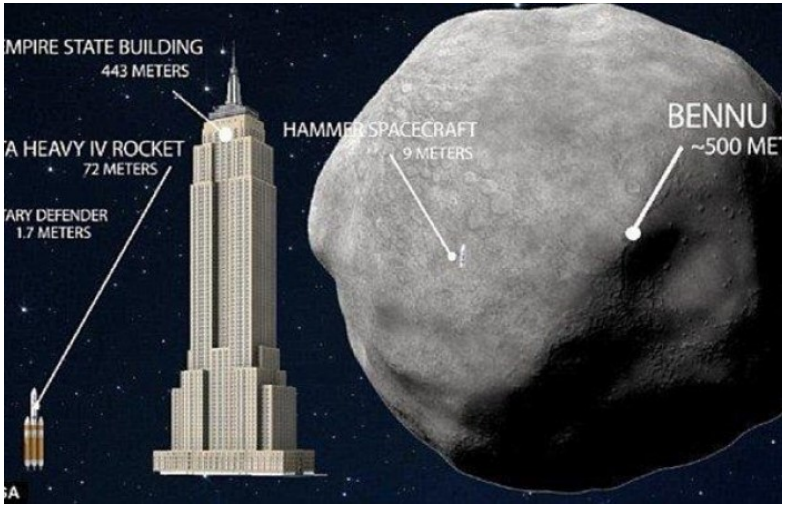
Yarkovsky Effect



- **Nuclear Explosion**: Efficient but controversial
- **Kinetic Impactor**: Feasible but not efficient (for large asteroids)

1 Research Backgrounds

- To deflect a large asteroid, the deflection performance of a kinetic impactor is limited.

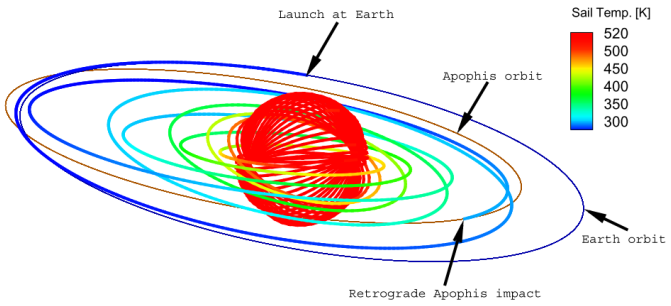


To deflect Bennu for 1.4 Earth radii

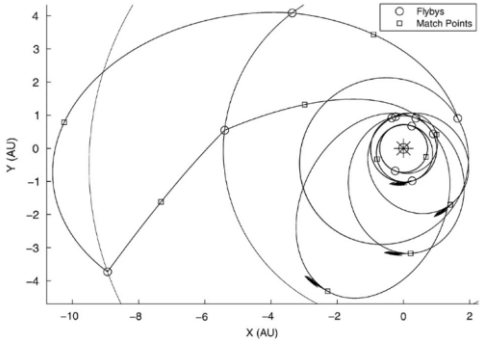
Warning Time	Number of Launches
25 years	17 Delta IV
10 years	75 Delta IV

(Barbee , 2018)

- Reversal orbit, H-reversal orbit concepts are used to improved deflection efficiency.



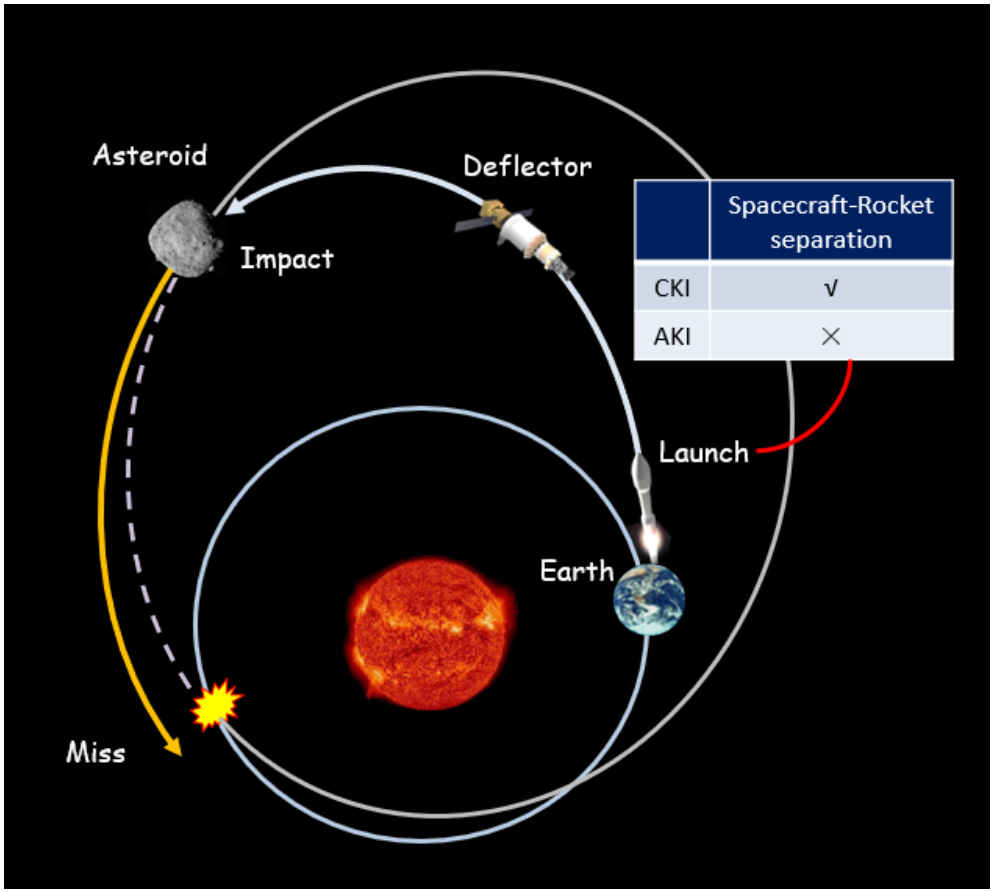
(Dachwald, 2007)



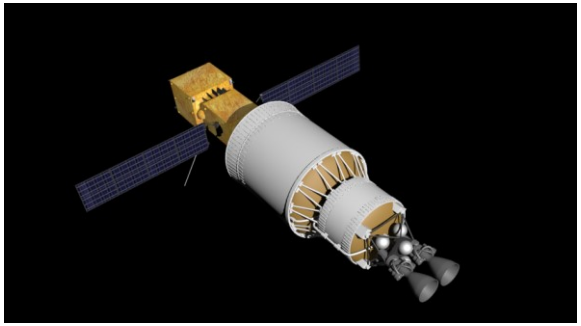
(Petropoulos, 2007)

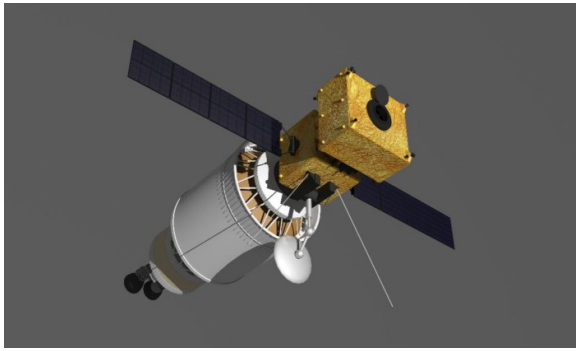
2 Concept of Assembled Kinetic Impactor

- The upper stage can be used as a payload to improve the mass of the impactor
  - The mass of Long March 5 upper stage: 6.5 tons



	Spacecraft-Rocket separation
CKI	√
AKI	×





3 Simulation Methods

- Compare **Assembled Kinetic Impactor (AKI)** with **Classic Kinetic Impactor (CKI)**

Deflection performance in a 10-year launch lead-time:

1. **Maximum deflection distance** of a single impactor
2. **Minimum number of launches** of 1.4 RE deflection distance

– Dynamic model

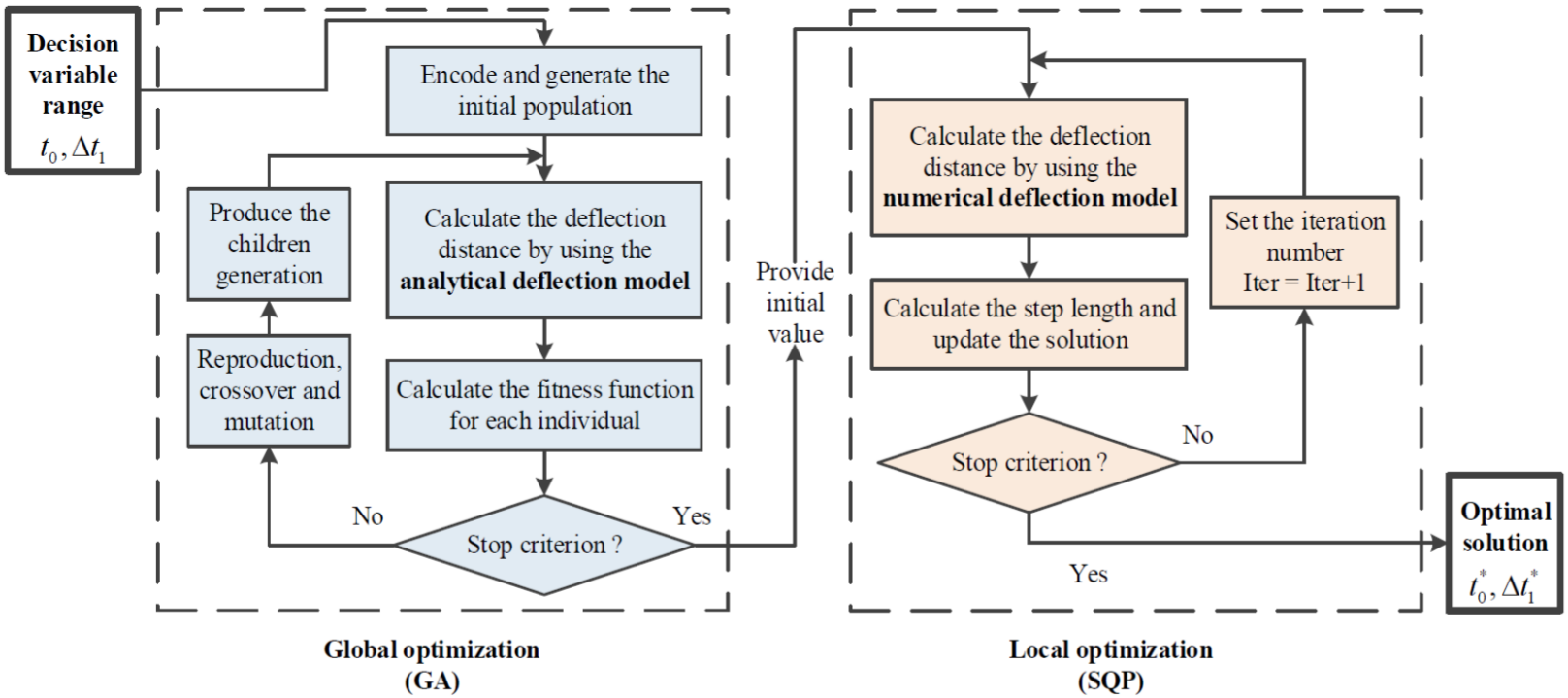
$$\frac{d^2\boldsymbol{r}}{dt^2} = -\frac{\mu_s}{|\boldsymbol{r}|^3}\boldsymbol{r} - \sum_{i=1}^{8}\mu_{pi}\left(\frac{1}{|\boldsymbol{d}_{pi}|^3}\boldsymbol{d}_{pi} + \frac{1}{|\boldsymbol{\rho}_{pi}|^3}\boldsymbol{\rho}_{pi}\right) + \boldsymbol{a}_{moon} + \boldsymbol{a}_{GR} + \boldsymbol{a}_{SRP} + \boldsymbol{a}_{YE}$$

– Impact model

$$\Delta\boldsymbol{v}_{Ast} \approx \beta\frac{m_{AKI}}{m_{AKI}+m_{Ast}}(\boldsymbol{v}_{AKI} - \boldsymbol{v}_{Ast})$$

3 Simulation Methods

– Optimization methods: Genetic Algorithm + Sequential Quadratic Programming



4 Simulation Results

- Deflection Object: Bennu

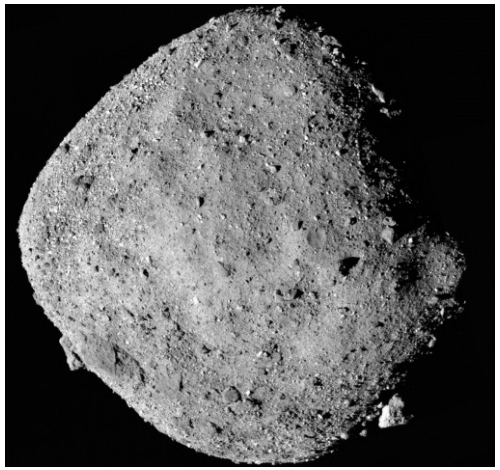
  Diameter: 492 m

  Mass: 7.9×10^{10} kg

  Closest Approach Date: 2135-9-25

  Closest Approach Distance: 0.00199 AU

  Ephemeris: JPL Horizons On-Line Ephemeris System



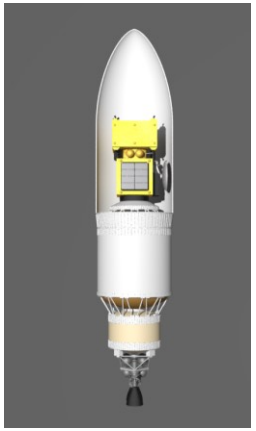
(Image Credit: OSIRIS-REx)

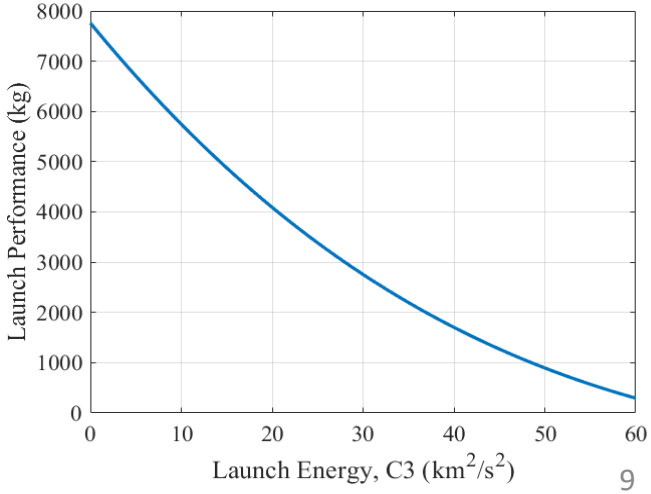
- Launch Vehicle: Long March 5

  Dry mass of upper stage: 6.5 tons

  Fairing diameter: 5.2 m

  Fairing height: 12.7 m





4 Simulation Results

- **Maximum deflection distance** of a single impactor

	CKI (Without Upper stage)	AKI (With Upper stage)
Launch Vehicle	CZ-5	CZ-5
Number of Launches	1	1
C3	13.75 km^2/s^2	42.89 km^2/s^2
Impactor Mass	5.09 tons	8.75 tons
Spacecraft Mass	5.09 tons	2.25 tons
Launch Date	2125-1-13 9:7:34	2125-1-27 6:44:25
Flight Time	651.14 days	1057.31 days
Impact Date	2126-10-26 12:24:19	2127-12-20 14:9:41
Impact Velocity	4.15 km/s	7.17 km/s
Bennu Δv	0.27 mm/s	0.79 mm/s
Deflection Time	3256.89 days	2836.82 days
Deflection Distance	**113.57 km**	**399.34 km**

- Compared with the CKI, the addition of the upper stage mass can increase the deflection distance **to more than 3 times**.

4 Simulation Results

- **Minimum number of launches** of 1.4 RE deflection distance

	CKI (Without Upper stage)	AKI (With Upper stage)
Launch Vehicle	CZ-5	CZ-5
Number of Launches	79	23
C3	13.78 km2/s2	43.00 km2/s2
Impactor Mass	401.41 tons	200.96 tons
Launch Date	2125-1-12 1:6:5	2125-1-26 14:27:40
Flight Time	651.65 days	1056.72 days
Impact Date	2126-10-25 16:44:14	2127-12-19 7:45:45
Impact Velocity	4.15 km/s	7.15 km/s
Bennu Δv	21.08 mm/s	18.18 mm/s
Deflection Time	3257.71 days	2838.08 days
Deflection Distance	1.41 Re (8988.86 km)	1.45 Re (9224.73 km)

- Compared with the CKI, the addition of the upper stage mass can reduce the required number of launches **from 79 to 23** for the CZ-5.

4 Simulation Results

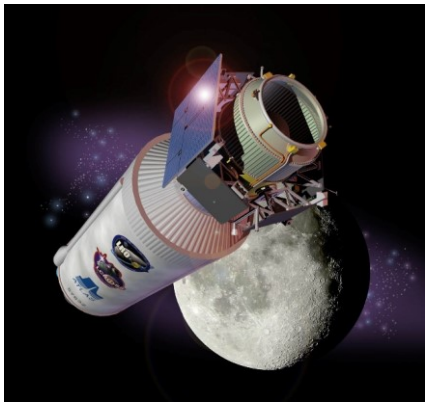
- Deflection performance of a **140 m diameter asteroid** with a 10-year launch lead-time

	CKI (Without Upper stage)	AKI (With Upper stage)
Launch Vehicle	CZ-5	CZ-5
Number of Launches	1	1
C3	13.76 km^2/s^2	42.94 km^2/s^2
Impactor Mass	5.08 tons	8.74 tons
Launch Date	2125-1-13 23:55:12	2125-1-26 18:33:17
Flight Time	651.37 days	1057.26 days
Impact Date	2126-10-27 8:49:55	2127-12-20 0:43:30
Impact Velocity	4.15 km/s	7.16 km/s
Bennu Δv	11.65 mm/s	34.57 mm/s
Deflection Time	3256.04 days	2837.38 days
Deflection Distance	**0.78 Re (4965.44 km)**	**2.75 Re (17538.81 km)**

- A single CKI **can't achieve a deflection distance of 1 Earth radii**, which cannot eliminate the threat of the asteroid impact.
- A single AKI **can achieve a deflection distance of 2.75 Earth radii**.

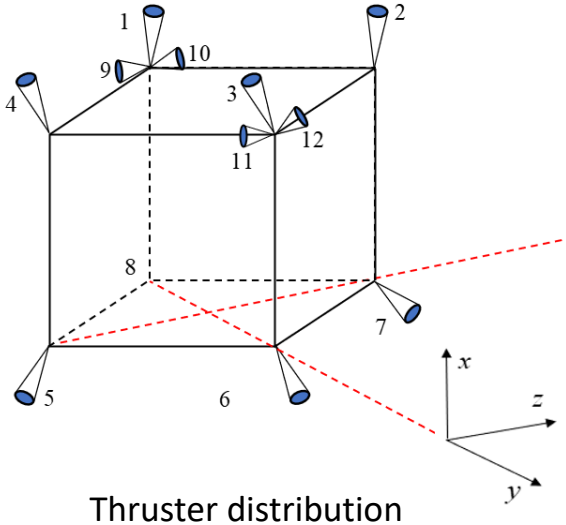
5 Technical Feasibility

- Challenges
  - avoid the coupling of attitude control and orbit control;
  - the center of mass of the AKI is located on the upper stage;
  - prevent the thruster plumes from affecting the solar arrays and upper stage

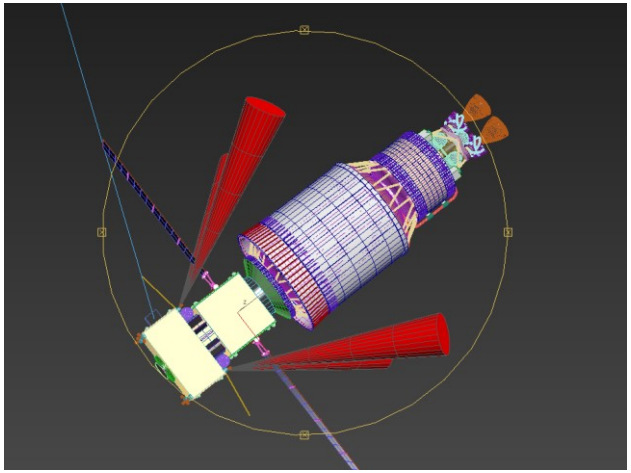


(Image Credit: LCROSS)

- An AKI platform is preliminarily designed



Thruster distribution

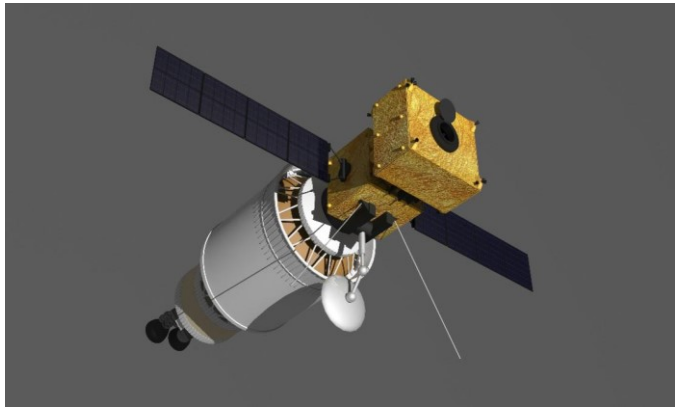


Analysis diagram of the thruster plumes

6 Conclusions

The **Assembled Kinetic Impactor (AKI)** is proposed, the missions of deflecting Bennu are designed to demonstrate the power of the AKI concept. Based on the technical data of the Long March 5 (CZ-5) launch vehicle, compared with the Classic Kinetic Impactor (CKI):

- The AKI concept can greatly **improve the deflection efficiency**, **reduce the launch cost**;
- The deflection distance of a **140 m diameter asteroid within 10 years**, can be increased **from less than 1 Earth radii to more than 1 Earth radii**.



Thanks for Your Attention!

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