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A tale of three teams: Effect of long-term isolation in SIRIUS-21 on crew interpersonal networks

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ABSTRACT

Crews venturing into deep space need to develop and maintain positive working relationships, and avoid negative ones. Effective crews need to maintain high levels of motivation, leadership, and viability, while minimizing hindrance relations among the crew. Applying social network theory and methods, we explore three topological aspects of team social relations found to predict their capacity to perform effectively. These include (1) the level of interconnectedness among the crew, (2) the degree to which the crew shows hierarchy, and variation on status, position, or power, and (3) the extent to which the crew shows subgrouping among members. In this study we investigated crew relations over time during Nazemnyy Eksperimental'nyy Kompleks (NEK) SIRIUS-21 mission, and compared their relations to two non-isolated control "twin teams." All three teams were observed for 8 months in order to understand developmental patterns in crew relations, and how these patterns are affected by extended isolation. Results show that there are substantial differences between SIRIUS-21 crew and control teams. The motivation ties were strongest in SIRIUS-21 as compared to non-isolated controls. At the same time, SIRIUS-21 experienced the most hindrance. Importantly, the loss of one SIRIUS-21 crew member on mission day 32 was associated with degraded crew networks, creating subgroups that persisted for the duration of the mission.

1. Introduction

When asked about the most important skills required for her job, astronaut Jessica Meir described: "I like to think about this along the lines of a camping trip and who you would like to have along with you … someone that is competent and can take good care of themselves and their equipment, someone that contributes to the team and helps with group tasks, someone that is good natured and pleasant to be around, etc., someone fun!"

For future long distance space exploration missions, it is critical to understand not only which teams can work together well, but also which teams can live together, rely on one another for support, and lead one another [1]. In these ways, space explorations may challenge crews in unique or unexpected ways they have never been before. Crews venturing into deep space need to develop and maintain positive working relationships and avoid negative ones. As missions move beyond low Earth orbit and crews become more Earth-independent, it is essential to monitor and mitigate team risk or the risk of mission failure due to inadequate cooperation within a team.

Research on teams finds interpersonal relationships and team processes overall consistently predict team performance [2]. Recent work suggests that a social network approach offers new insights into the patterns of relationships and how they affect performance in small groups in general [2] and in space crews in particular [3]. Network closure, centralization, and subgrouping provide a useful way to detect changes in team relations so interventions can be used to restore team relations. First, social network research suggests that *closure*, which reflects the degree to which team members see one another as valuable and instrumental to the work, increases team effectiveness and performance [4]. Closed networks offer more opportunities for a high level of information sharing, which allows team members to coordinate work [5,6] and effectively accomplish tasks [7–10]. For example, research on eight four-person crews that completed analog space missions between January 2016 and June 2018 found that densely configured positive working networks (i.e., "who do you enjoy working with?") are associated with high performance on tasks, such as execute tasks (i.e., simulation tasks in which two crew members use a joystick to fly a transit vehicle to collection sites, while the other two crew members use

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virtual reality goggles to complete Extra Vehicular Activity exploring an asteroid's surface) [3].

Second, the degree to which the teams show hierarchy, and variation in status, position, or power affects team performance. Network theories on teams operationalize hierarchy, power, or position in teams using *centralization*. Centralization defines how team interactions, such as communication or leadership, are concentrated around one or a few team members [11,12]. Team members with high centrality control the information flow [13,14] and their incapacitation produce bottlenecks in the flow of communication and harm the team [15]. Centralization [12] has also been applied to leadership research to capture the degree of differentiation among team members in providing informal leadership [2,16]. Separately, research on space analogs showed that teams with leadership concentrated on one person (i.e., hierarchical leadership) and not shared among crew members (i.e., shared leadership) will develop less team-shared mental model [17], which in turn will negatively influence team performance [18].

Finally, *subgrouping* in network theory represents the degree to which team relationships are concentrated among subsets of members along with a reduced number of connections between subsets [12]. Subgrouping within a team negatively influences team performance because team members are unable to integrate diverse knowledge [19]. Furthermore, teams characterized by subgrouping, or factions, might develop different mental models [20,21] negatively affecting team performance [22]. Subgroups form on different bases (e.g., driven by social identity processes, social dominance processes, or information-processing processes) [19], and early identification will offer possibilities for interventions to restore team relations.

Crews venturing into deep space will be composed of members of different gender, age, nationality, and therefore, they will be more susceptible to subgrouping. For example, research on three crews that spent between 110 and 240 days in isolation at Institute for Biomedical Problems in Moscow found that two crews were not able to create a cohesive group due to gender and language differences [23,24]. Similarly, research on a 105-day confinement study in which a multinational crew simulated a Mars mission (i.e., MARS-105) found subgrouping formed based on personal values [25].

In this study, we apply social network theory and methods to explore the three topological aspects of teams found to predict their capacity to perform effectively: (1) the level of interconnectedness among the crew, (2) the degree to which the crew shows hierarchy, and variation on status, position, or power, and (3) the extent to which the crew shows subgrouping among members. We focus on four crew social relationships: motivation, leadership, hindrance, and viability. First, team motivation indicates the strength of the social influence within the crew, the degree to which one member's actions affect another's goal-directed activities. Second, team leadership is pivotal to mission success, providing direction, enabling creative thinking, minimizing conflicts, negotiating across expertise, and maintaining high levels of motivation throughout the mission. Third, hindrance, or negative relations, have been shown to affect crew performance negatively [3]. Fourth, viability captures the satisfaction of team members with their team membership and their behavioral intent to remain in their team [8,26,27]. And crew member beliefs about team viability will influence the crew's "capacity for the sustainability and growth required for success in future performance episodes" [28].

We observed the crew relationships in the Nazemnyy Eksperimental'nyy Kompleks (NEK) 8-month SIRIUS-21 mission, to better understand how crew relations develop over time in isolation. And to enable some degree of comparison to how these relations might develop outside isolation, we recruited two "twin teams" who performed the same team-based tasks and survey measures over the same 8-month period. Our research questions are twofold: (1) How do crew relations develop and change over time in isolation? and (2) To what extent are relations similar to and different from those that might be observed among teams not in isolation?

2. Methods

The data used in this study were collected from three teams who were all participating in the study from November 2021 to July 2022. The SIRIUS-21 crew lived in the NEK analog and the two twin teams were located at Northwestern University, a U.S. research university.

2.1. NEK SIRIUS-21

NEK is a controlled, isolated environment at the Institute of Biomedical Problems at the Russian Academy of Sciences in Moscow, Russia. NEK is specifically designed to measure the unique consequences of isolation, as well as other psychological and physical stressors on space missions. Crew members in the NEK analog are isolated and have limited and delayed communication with the outside world. Fig. 1 presents a photo of the exterior views of the NEK research analog facility.

We report data on crew relationships during SIRIUS-21. SIRIUS-21 was an international mission with the space agencies of the United States, Russia, and United Arab Emirates to study the effects of isolation and confinement in long-duration space missions. SIRIUS-21 simulated a lunar mission consisting of four phases: a transit phase, various surface operations, lunar orbit, and return to Earth. Throughout the mission, the crew took part in many tasks and experiments designed to understand better the effects of isolation on different aspects of space travel. The SIRIUS-21 mission took place from November 2021 to July 2022 and began with a 6-person crew composed of three Russians, two Americans, and one Emirati, and included three women and three men. Each crew member performed a unique role: commander, flight engineer, crew surgeon, and three mission specialists. Fig. 2 shows the picture of the SIRIUS-21 crew.

An important off-nominal event occurred on Mission Day 32 (MD32). The Mission Specialist 2 (MS2) injured her right elbow while performing a strength test on a training machine. Other crew members initially treated the injury in consultation with medical professionals from the Institute of Biomedical Problems of the Russian Academy of Sciences. A portable x-ray machine was brought in to assess the injury. It was determined that the crew member suffered a closed fracture of the humerus bone with displacement. After an investigation, it was determined that the injury was caused by equipment malfunction, user error, and lack of appropriate oversight and training. It was decided that the MS2 would need hospitalization for further diagnosis, surgery, and rehabilitation. This meant that the crew member would have to leave isolation and the mission would continue with five crew. The remaining crew was comprised of two women and three men, two from Russia, 2 US, and one Emirati.

2.2. Non-isolated control "twin teams"

In conjunction with the NEK SIRIUS-21 mission, we assembled two "twin teams" composed of undergraduate students to participate in the same team and multiteam exercises as the SIRIUS-21 crew outside of isolation. The undergraduate students were recruited from Northwestern University. The qualifications for recruitment were designed to mirror those of the SIRIUS-21 mission. Specifically, we looked for students with science, technology, engineering, and mathematics backgrounds and/or military experience and enthusiasm for the project. Potential participants were asked to fill out a recruitment survey that asked questions about their background and availability, and questions designed to gauge interest. These questions included: "Why do you want to participate?", "What makes you a good team member?", and "Would you consider going to Mars?"

After identifying those whose backgrounds matched our criteria and meeting with the students to explain the project's demands, we composed two teams: TWIN-BLACK and TWIN-SILVER. Each team was constructed to have the most diversity among backgrounds, gender,

Fig. 1. Photograph of the exterior of the NEK Analog (Moscow, Russia); Image credits: NASA.

Fig. 2. SIRIUS-21 Crew; Image credits: NASA.

race, and nationality. Each team had seven members to correspond to each of the SIRIUS-21 crew roles plus one backup crew member. Fig. 3 shows the picture of the two twin teams, and Table 1 compares the composition of the three teams.

Fig. 3. TWIN-BLACK and TWIN-SILVER teams.

2.3. Team and multiteam tasks

While in isolation, the SIRIUS-21 crew participated in various team tasks designed to evaluate different aspects of team performance. These tasks include a weekly team task battery that contains tasks related to problem-solving, ethical decision-making, and creativity [29], and a group decision-making task entitled hidden profiles [30] given five times throughout the eight months. Additionally, the non-isolated twin teams met at least once per week, either in-person at a research laboratory at Northwestern University or online using Zoom, depending on the Northwestern University academic calendar, to conduct the same team tasks as the SIRIUS-21 crew for the duration of the eight-month mission. The twin teams would meet once a week for an hour to take part in the team task battery. The twin teams also met for five additional hours spread throughout the 8 months to complete the hidden profile decision-making task.

Every two weeks, the SIRIUS-21 crew participated in two multiteam tasks synchronously with one of the twin teams or the other, alternating

Table 1
Team composition.

	SIRIUS-21	TWIN-BLACK	TWIN-SILVER
Location	NEK	Northwestern University	Northwestern University
Members	6	6 + 1 backup	6 + 1 backup
Gender	3 M/3F	3 M/3F + 1 M	3 M/3F +1F
Non-White	1	4	5
Non-US	4	2	2
Education/ Expertise	Mechanical Engineering	Mechanical Engineering	Mechanical Engineering
	Mechanical and Aerospace Engineering	Mechanical Engineering	Industrial Engineering
	Medicine	Music and Pre-Medicine	Psychology
	Computer Science	Chemistry	Computer Science
	Journalism	Applied Mathematics	Journalism
	Military Aviation	Materials Science	Mathematical Methods
		Journalism	Applied Mathematics

each time. First, the Project RED Design task is a computer-based task requiring a 12-person multiteam system to collaborate to build a hypothetical well to sustain a Mars population [10]. The participants are assigned to one of the four disciplinary teams (i.e., geology, robotics, human factors, and engineering). Each disciplinary team contained at least one SIRIUS-21 crew member. Participants performed the task for 45 min.

The Project RED Design task was followed by the Project RED Relay task where the SIRIUS-21 crew and the twin team engaged in a network routing task [31]. The task required participants to choose two direct contacts (from 11 others) to relay messages sent by Jet Propulsion Lab to a destination to implement a decision. The SIRIUS-21 crew and the twin team then attempted to route messages they received directly from Jet Propulsion Lab (or indirectly via others who chose them as direct contacts in the activity) to the final destination. Participants engaged in two rounds of this activity, each lasting 10 min.

2.4. Sociometric network survey

We leveraged a dyadic measurement perspective using network surveys to assess relations among all possible dyads. The sociometric network survey was administered twice a week for SIRIUS-21 crew and every week for the two twin teams. Each week, the twin team members were sent a survey with the same team dynamics questions that were asked of the SIRIUS-21 crew. The teams were sent the survey each Monday and were asked to complete it by the end of the day the following Sunday.

Network surveys elicited motivation, leadership, hindrance, and viability relations. Motivation was assessed with the prompt, “Who kept your taskforce motivated?” Leadership was assessed with the prompt, “Who did you rely on for leadership?” Hindrance was assessed with the prompt, “Who makes tasks difficult to complete?” and viability with the prompt, “With whom would you want to go on a 3-year space mission?”

3. Results

3.1. Interconnectedness within the crew and twin teams

To assess the interconnectedness in the SIRIUS-21 crew and the two twin teams, we used network density. Network density is operationalized as the number of observed ties divided by the number of possible ties. For example, in a network of 6 members, there are $6 \times 5 = 30$ possible directed ties from one member to another. Network density measures range from 0 (no observed ties in the network) to 1 (all ties are observed). Although the twin teams were asked to complete the network survey weekly, not all twin members responded. For the network density measure to be comparable across teams and time, we need complete data (i.e., all participants having responded to the network survey). Therefore, we kept only those network surveys that had a maximum two missing participants (out of 7 team members). This study measured the network density 69 times for SIRIUS-21, 24 times for the TWIN-BLACK team, and 16 times for the TWIN-SILVER team. Finally, to have at least one data point across all three teams at each point on analysis, we averaged the network densities across every three weeks, which gave us 11 data points. Ideally, we would have analyzed the data at a weekly level, but the missing data in the twin teams prohibited this.

Fig. 4 presents the interconnectedness across time for the motivation relation. Results showed that, overall, the crew motivation in SIRIUS-21 was higher than in the twin teams and remained higher throughout the 8-month period. A Wilcoxon Signed Rank Test was performed to determine if there was a statistically significant difference in the mean network density between the three teams. The test revealed that there was a statistically significant difference in mean network density between SIRIUS-21 and TWIN-BLACK ($z = 2.934$, $p = 0.003$), between SIRIUS-21 and TWIN-SILVER ($z = 2.936$, $p = 0.003$), and between TWIN-BLACK and TWIN-SILVER ($z = 2.269$, $p = 0.023$).

Fig. 5 presents the interconnectedness across time for the leadership relation. Results showed that, overall, the crew leadership in TWIN-SILVER was higher than in the TWIN-BLACK team and the SIRIUS-21 crew. A Wilcoxon Signed Rank Test was performed to determine if there was a statistically significant difference in the mean network density between the three teams. The test revealed that there was a statistically significant difference in mean network density between SIRIUS-21 and TWIN-SILVER ($z = -2.845$, $p = 0.004$), and between TWIN-BLACK and TWIN-SILVER ($z = -2.934$, $p = 0.003$). Examining Fig. 5 shows that a trend exhibited by all three teams was a decline in leadership density during the mission.

Fig. 6 presents the interconnectedness across time for the hindrance relation. Results showed that, overall, the crew hindrance in SIRIUS-21 was higher than in the twin teams. In SIRIUS-21, hindrance increased up until the point when the one crew member was unable to continue the mission, and then declined. But around mid-mission, SIRIUS-21 hindrance ties began to increase and did so until the end of the mission. A Wilcoxon Signed Rank Test was performed to determine if there was a statistically significant difference in the mean network density between the three teams. The test revealed that there was a statistically significant difference in mean network density between SIRIUS-21 and TWIN-BLACK ($z = 2.938$, $p = 0.003$), between SIRIUS-21 and TWIN-SILVER ($z = 2.936$, $p = 0.003$), and between TWIN-BLACK and TWIN-SILVER ($z = -2.572$, $p = 0.010$). Interestingly, hindrance relations were higher in the

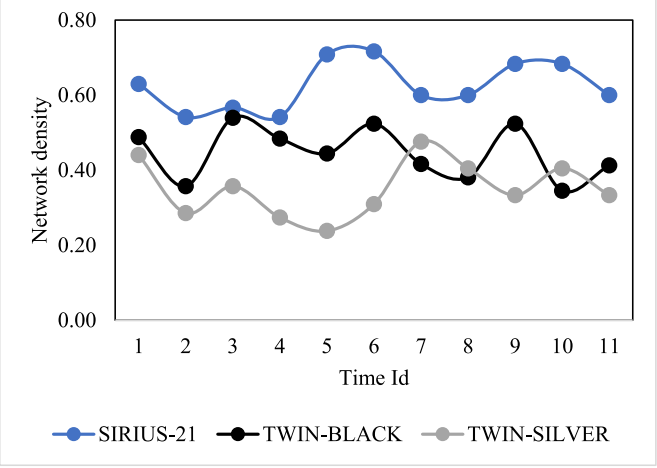

Fig. 4. Network density for motivation relation.

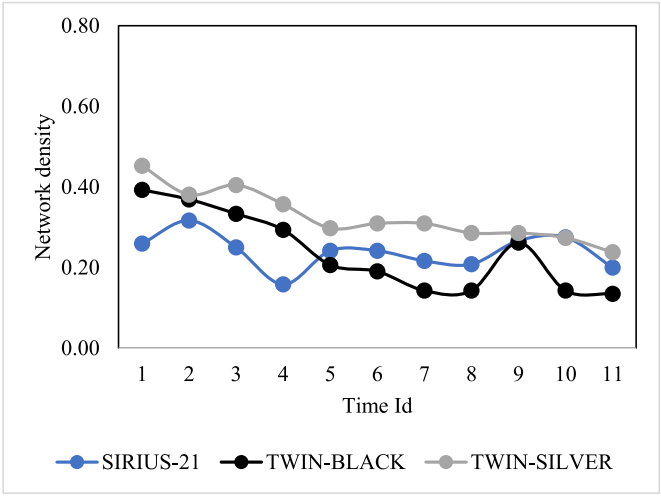

Fig. 5. Network density for leadership relation.

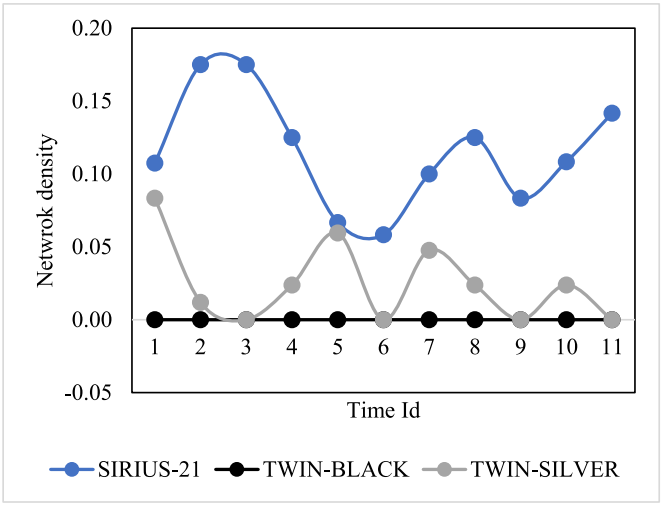

Fig. 6. Network density for hindrance relation.

SIRIUS-21 crew at every point during the mission.

Fig. 7 presents the interconnectedness across time for the viability relation. Results showed that there is high variability over time.

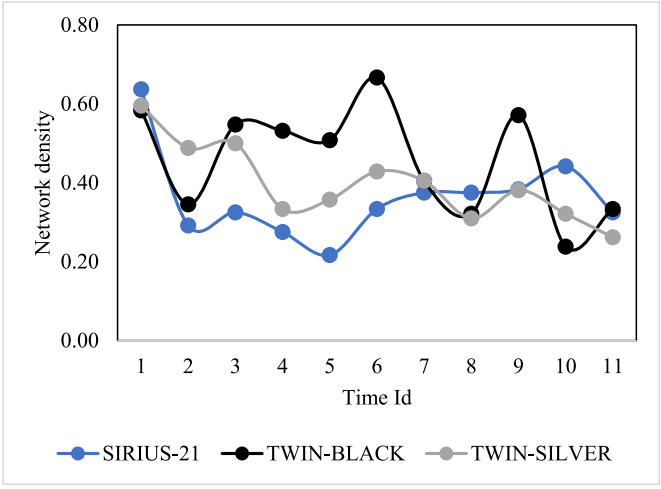

Fig. 7. Network density for viability relation.

However, there is no statistical difference between the three teams. All three teams showed an early decline in viability after the first measurements (Fig. 7, period 2), and the SIRIUS-21 crew showed continuing declines that persisted into period 7.

3.2. Crew hierarchy

To assess the degree to which the crew shows hierarchy we examined whether the SIRIUS-21 leadership relationship displayed a hierarchical or shared leadership structure [17]. While prior leadership network research operationalized leaders as team members with high in-degree centrality [e.g., 16], in this paper we define a crew member as a leader if they were nominated as leader by at least two other crew members (i.e., in-degree value of minimum 2). Over the course of the mission, a crew can have no leaders, one, two, three, four, five, or six leaders. At the crew level, a crew has a shared-coordinated leadership structure if there are at least two leaders in the crew and the two leaders rely on each other for leadership. A crew has a shared-fragmented leadership structure if there are at least two leaders in the crew and the two leaders do not rely on each other for leadership. A crew has a hierarchical leadership structure if there is only one leader in the crew, and has an absent leadership structure if there are no leaders. Fig. 8 presents examples of shared-coordinated (Fig. 8a), shared-fragmented (Fig. 8b), hierarchical (Fig. 8c), and absent (Fig. 8d) leadership structures.

Crew leadership over time showed interesting patterns. Before MD32, when MS2 left the mission, the crew exhibited the optimal shared-coordinated leadership structure. After MD32, the leadership structures alternated between three suboptimal archetypes: hierarchical (67%), shared-fragmented (27%), and absent (7%).

3.3. Crew subgrouping

Finally, to examine the extent to which the SIRIUS-21 crew showed subgrouping among members we used the relation viability. Similar to

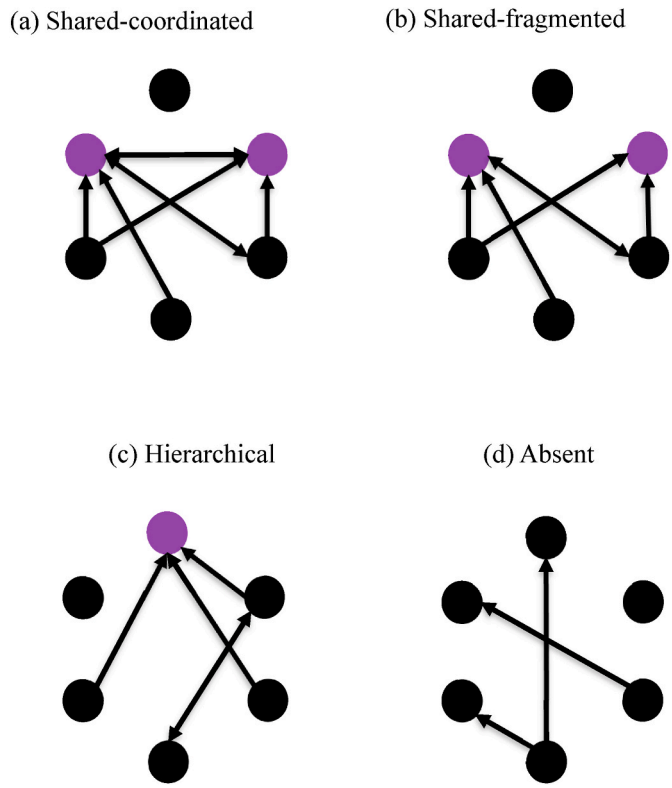

Fig. 8. Leadership structure.

the leadership results, the crew displayed different patterns before and after MD32.

Before MD32, crew members selected each other as someone who would want to go on a 3-year space mission (see Fig. 9 a). After MD32, two subgroups emerged. The two members in subgroup 1 reciprocated the viability relation between the two of them. The two members in subgroup 2 did not select anyone to be a partner in a future mission, not even each other. Finally, there was a crew member who selected everyone, and sometimes reciprocated with one crew member from subgroup 1 (see Fig. 9 b).

4. Discussion

Developing and maintaining positive working relationships, and avoiding negative ones are important conditions for crew performance. Performance on deep space exploration missions will require positive sustained crew relations through an extended period of time spent living and working together in an isolated and confined environment. Furthermore, deep space exploration missions will necessitate a degree of crew autonomy to succeed that has not been required of any previous missions.

The current study provides an important look at how social relations most critical to performance develop and change over time in isolation. Three strengths of this research are the long-time duration, the cultural diversity of the SIRIUS-21 crew, and the inclusion of two non-isolated control teams completing the same team tasks and measures as an entity over time.

The first contribution of this study is to compare crew networks among the SIRIUS-21 crew to those of two "twin teams" outside of an isolated and confined environment. Table 2 presents a summary of the best and worst teams across the four social relations. The SIRIUS-21 crew had the strongest effect on one another's motivation, while the TWIN-SILVER team had the least effect. However, the TWIN-SILVER team relied on each other for leadership more than SIRIUS-21 and TWIN-BLACK teams. Next, TWIN-BLACK encountered the least difficulties (i.e., hindrance relation) and was the most viable team. On the other hand, SIRIUS-21 crew encountered the most difficulties among the crew members and was the least viable team.

Table 3 presents the patterns observed in social relations over time. In addition to differences in the amount/density of social relations in the three crews, we also observed different patterns in the hindrance networks for the SIRIUS-21 crew as compared to the two twin teams. In SIRIUS-21, hindrance was highest (worst for performance) early and late mission, and at its lowest (best for performance) mid mission. The twin teams did not exhibit this pattern. While prior research on isolated groups in Antarctica identified a third-quarter phenomenon, characterized by strenuous social interactions [32,33], research on long duration isolation space analogs, such as MARS-500, did not identify any quarter effects [34,35]. Distinct from the Antarctica studies, the crew in MARS-500 reported positive emotions and group cohesion gradually increasing over time. SIRIUS-21 crew members did not follow the patterns noticed in previous studies, but their hindrance relations vary over time, with the highest values being noticed early and late mission.

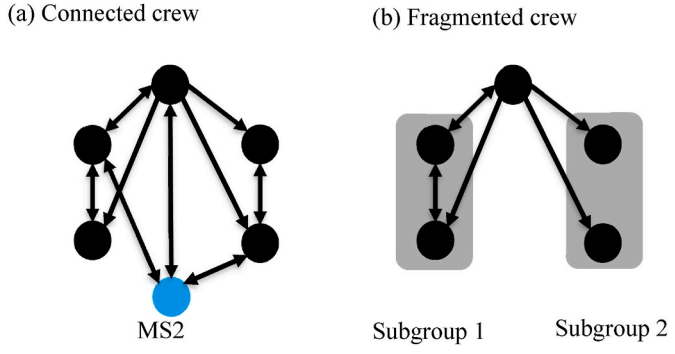

Fig. 9. Viability relation (a) before and (b) after MD32.

Table 2
Social relations: Best vs. worst team.

Crew relation	Best	Worst
Motivation	SIRIUS-21	TWIN-SILVER
Leadership	TWIN-SILVER	SIRIUS-21/TWIN-BLACK
Hindrance	TWIN-BLACK	SIRIUS-21
Viability	TWIN-BLACK	SIRIUS-21

Table 3
Social relations: Pattern over time.

Crew relation	Pattern in SIRIUS-21 vs TWIN teams	Trends
Motivation	Similar	Small fluctuations over time
Leadership	Similar	The leadership relationship is declining. The loss of the crew member MS2 moved the leadership relation in SIRIUS-21 from connected to disconnected.
Hindrance	Not similar	There was little variation in TWIN teams. SIRIUS-21 crew presented wide variations with mid-mission being the best (lowest hindrance density).
Viability	Similar	The loss of the crew member MS2 triggered formation of two subgroups in SIRIUS-21 crew.

The second contribution of this study is to understand the effect of the off-nominal event on MD32 on crew relations. It is important to note that the off-nominal event disturbed the patterns of social relationships in SIRIUS-21 crew. The loss of the crew member MS2 moved the leadership relationship from connected to disconnected. Whereas prior to MD32, the crew had two strong leaders who were reciprocating leadership among them, following MD32, the two leaders remained, but were no longer coordinated. The relationship never recovered.

The implications of this for crew relations are borne out in the viability networks where we observed two clear subgroups through the remainder of the mission. The loss of the crew member MS2 triggered the formation of two subgroups in SIRIUS-21 crew: one subgroup that was still willing to go on a 3-year space mission with each other, and one subgroup that did not want any other involvement in future missions together. Debriefs with the crew post-mission suggest the crew was aware of this subgrouping.

One point that bears mention is that the subgroups were not formed along cultural or gender lines. These findings differ from results in previous space isolation studies which showed subgrouping and intra-crew tension generated by cultural and gender differences [23–25,36]. The results from SIRIUS-21 are similar to the SIRIUS-19 mission results where no subgrouping was found, even though the multinational crew spent 4 months in isolation [37,38]. Indeed, the subgrouping in SIRIUS-21 appears related to tensions related to the off-nominal event. Each of the viability subgroups in SIRIUS-21 consisted of one Russian and one US crew member. Despite the harmful effect of subgroups in the crew, the finding that they did not form along cultural or gender faultlines is a positive finding. Nonetheless, the formation of such strong subgroups for the duration of the mission highlights the need for future research to better understand the mechanisms behind subgroup formation and interventions to reduce or prevent it so as not to compromise crew performance.

The third contribution of this study is to illustrate how social network theory and methods can be used to monitor and investigate crew relations during space missions. We study three topological aspects of teams found to predict their capacity to perform effectively: the interconnectedness among the crew, the crew hierarchical leadership structure, and the crew subgrouping.

5. Conclusion

In conclusion, results from this study show that there are substantial differences between SIRIUS-21 crew and the non-isolated twin teams. The SIRIUS-21 crew had the strongest effect on one another's motivation of the three teams. At the same time, SIRIUS-21 encountered the most difficulties among the crew members and was the least viable team. Importantly, the loss of a crew member disturbed the patterns of social relationships in SIRIUS-21 and triggered the formation of two subgroups that persisted until the end of SIRIUS-21.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Acronyms/Abbreviations

Nazemnyy Eksperimental'nyy Kompleks: (NEK)